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EVALUATION OF LASER-PROTECTION EYEWEAR

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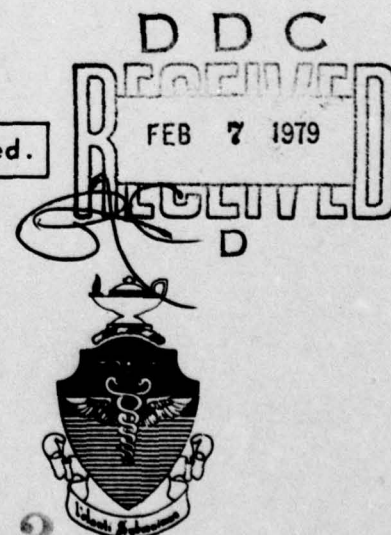
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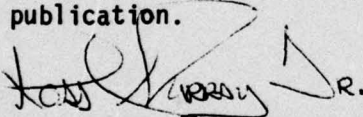
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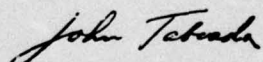
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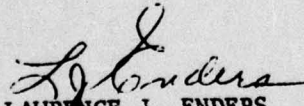
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PREFACE

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CONTENTS

| | <u>Page</u> |
|--|-------------|
| INTRODUCTION..... | 7 |
| EYEWEAR CHARACTERISTICS..... | 7 |
| Design Parameters..... | 8 |
| Laser Beam Visibility..... | 9 |
| Filter Breakdown..... | 9 |
| Style of Protectors..... | 10 |
| Spectacles with Side Shields..... | 10 |
| Flexible Goggles with Glass Lenses..... | 10 |
| Headrest Flexible Goggles..... | 10 |
| Coverall-Type Flexible Vinyl Goggles..... | 10 |
| Full-view Soft Vinyl Goggles..... | 10 |
| Full-view Hard Plastic Spectacles with Side Shields..... | 11 |
| Air Force Visor..... | 11 |
| Air Force Aircrew Spectacles..... | 11 |
| TESTING METHODOLOGY..... | 11 |
| Introduction..... | 11 |
| Optical Quality Under Nonstress Conditions..... | 12 |
| Dimension Standards..... | 12 |
| Spectrophotometry..... | 12 |
| Luminous Transmittance..... | 13 |
| Laser Densitometer..... | 13 |
| Haze..... | 14 |
| Refractive and Prismatic Effects..... | 14 |
| Optical Quality Under Stress Conditions..... | 14 |
| Environmental Effects--Spectral and Physical..... | 14 |
| Shelf-Life Studies..... | 15 |
| Laser-Induced Damage..... | 15 |
| CO ₂ Exposures..... | 15 |
| Argon Exposures..... | 16 |
| Ruby Exposures..... | 16 |
| Irreversible Transmittance..... | 17 |
| Reversible Transmittance..... | 17 |
| Fume Analysis..... | 18 |
| Impact Resistance..... | 19 |
| RESULTS AND DISCUSSION..... | 19 |
| Optical Quality Under Nonstress Conditions..... | 19 |
| Dimensions..... | 19 |
| Spectrophotometry..... | 20 |
| Optical Density..... | 20 |
| Haze..... | 21 |
| Refractive and Prismatic Effects..... | 21 |
| Luminous Transmittance..... | 21 |
| Optical Quality Under Stress Conditions..... | 22 |
| Environmental Effects..... | 22 |
| Shelf-Life Study..... | 23 |
| CO ₂ Exposures..... | 23 |
| Argon Exposures..... | 24 |
| Ruby Exposures..... | 25 |
| Irreversible Transmittance..... | 26 |
| Reversible Transmittance..... | 26 |
| Fume Analysis..... | 27 |
| Impact Resistance..... | 27 |
| CONCLUSIONS..... | 27 |
| Optical Quality Under Nonstress Conditions..... | 27 |
| Optical Quality Under Stress Conditions..... | 28 |
| RECOMMENDATIONS..... | 29 |
| REFERENCES..... | 29 |

LIST OF ILLUSTRATIONS

| Figure | | |
|--------|---|----|
| 1. | Relative spectral luminous efficiency of the human eye..... | 31 |
| 2. | Spectacles with side shields..... | 32 |
| 3. | Flexible goggles with glass lenses..... | 32 |
| 4. | Headrest flexible goggles..... | 33 |
| 5. | Coverall-type flexible vinyl goggles..... | 33 |
| 6. | Full-view soft vinyl goggles..... | 34 |
| 7. | Full-view hard plastic spectacles with side shields..... | 34 |
| 8. | Air Force aircrew helmet with laser-protection visor..... | 35 |
| 9. | Air Force aircrew spectacles..... | 35 |
| 10. | Pulsed laser densitometer..... | 36 |
| 11. | Environmental chamber's energy distribution curve..... | 37 |
| 12. | CO ₂ damage threshold experimental apparatus..... | 38 |
| 13. | Argon damage threshold experimental apparatus..... | 39 |
| 14. | Ruby damage threshold/irreversible bleaching experimental apparatus..... | 40 |
| 15. | Arrangement of apparatus for measurement of reversible bleaching..... | 41 |
| 16. | Arrangement of apparatus for beam scan measurement for reversible bleaching experiment..... | 42 |
| 17. | CO ₂ fume analysis experimental apparatus..... | 43 |
| 18. | Environmental effects--AO 580-UV-visible range..... | 44 |
| 19. | Environmental effects--AO 580-NIR range..... | 44 |
| 20. | Environmental effects--AO 581-UV-visible range..... | 45 |
| 21. | Environmental effects--AO 584-UV-visible range..... | 45 |
| 22. | Environmental effects--AO 584-NIR range..... | 46 |
| 23. | Environmental effects--AO 585-UV-visible range..... | 46 |
| 24. | Environmental effects--AO 585-NIR range..... | 47 |
| 25. | Environmental effects--AO 586-UV-visible range..... | 47 |
| 26. | Environmental effects--AO 586-NIR range..... | 48 |
| 27. | Environmental effects--AO 588-UV-visible range..... | 48 |
| 28. | Environmental effects--AO 588-NIR range..... | 49 |
| 29. | Environmental effects--AO 598-UV-visible range..... | 49 |
| 30. | Environmental effects--AO 599-UV-visible range..... | 50 |
| 31. | Environmental effects--AO 680-IR range..... | 50 |
| 32. | Environmental effects--AO 698-UV-visible range..... | 51 |
| 33. | Environmental effects--AO 688-NIR range..... | 51 |
| 34. | Environmental effects--AO window laminate-UV-visible range..... | 52 |
| 35. | Environmental effects--AO window laminate-NIR range..... | 52 |
| 36. | Environmental effects--BL 5W3754-UV-visible range..... | 53 |
| 37. | Environmental effects--BL 5W3755-UV-visible range..... | 53 |
| 38. | Environmental effects--BL 5W3755-NIR range..... | 54 |
| 39. | Environmental effects--BL 5W3756-UV-visible range..... | 54 |
| 40. | Environmental effects--BL 5W3757-NIR range..... | 55 |
| 41. | Environmental effects--BL 5W3758-NIR range..... | 55 |
| 42. | Environmental effects--FS AL-515-7-UV-visible range..... | 56 |
| 43. | Environmental effects--FS AL-633-5-UV-visible range..... | 56 |
| 44. | Environmental effects--FS AL-633-5-NIR range..... | 57 |
| 45. | Environmental effects--FS AL-1060-IR range..... | 57 |
| 46. | Environmental effects--GO LGA-UV-visible range..... | 58 |
| 47. | Environmental effects--GO LGA-NIR range..... | 58 |
| 48. | Environmental effects--GO LGB-UV-visible range..... | 59 |
| 49. | Environmental effects--GO LGB-NIR range..... | 59 |
| 50. | Environmental effects--GO LGS-A-UV-visible range..... | 60 |
| 51. | Environmental effects--GO LGS-HN-UV-visible range..... | 60 |
| 52. | Environmental effects--GO LGS-HN-SS-UV-visible range..... | 61 |
| 53. | Environmental effects--GO LGS-NDGA-UV-visible range..... | 61 |
| 54. | Environmental effects--GO LGS-NDGA-NIR range..... | 62 |
| 55. | Environmental effects--GO LGS-NDGA-SS-UV-visible range..... | 62 |
| 56. | Environmental effects--GO LGS-NDGA-SS-NIR range..... | 63 |
| 57. | Environmental effects--GO LGS-NN-UV-visible range..... | 63 |
| 58. | Environmental effects--GO LGS-NN-SS-UV-visible range..... | 64 |
| 59. | Environmental effects--GO LGS-R-UV-visible range..... | 64 |
| 60. | Environmental effects--GO LGS-R-SS-UV-visible range..... | 65 |
| 61. | Environmental effects--GO LGU-A-UV-visible range..... | 65 |
| 62. | Environmental effects--GO LGU-HN-UV-visible range..... | 66 |

CONTENTS (Continued)

Page

| | |
|---|-----|
| 63. Environmental effects--GO LGU-NDGA-UV-visible range..... | 66 |
| 64. Environmental effects--GO LGU-NDGA-NIR range..... | 67 |
| 65. Environmental effects--GO LGU-R-UV-visible range..... | 67 |
| 66. Environmental effects--GO A 7448-1-UV-visible range..... | 68 |
| 67. Environmental effects--GO A 7448-1-SS-UV-visible range..... | 68 |
| 68. Environmental effects--GO HN 7448-1-UV-visible range..... | 69 |
| 69. Environmental effects--GO HN 7448-1-SS-UV-visible range..... | 69 |
| 70. Environmental effects--GO NDGA 7448-1-UV-visible range..... | 70 |
| 71. Environmental effects--GO NDGA 7448-1-NIR range..... | 70 |
| 72. Environmental effects--GO NDGA 7448-1-SS-UV-visible range..... | 71 |
| 73. Environmental effects--GO NDGA 7448-1-SS-NIR range..... | 71 |
| 74. Environmental effects--GO R 7448-1-UV-visible range..... | 72 |
| 75. Environmental effects--GO R 7448-1-SS-UV visible range..... | 72 |
| 76. Environmental effects--HD 112-1-UV-visible range..... | 73 |
| 77. Environmental effects--HD 112-1-NIR range..... | 73 |
| 78. Environmental effects--HD 112-2-UV-visible range..... | 74 |
| 79. Environmental effects--HD 112-4-NIR range..... | 74 |
| 80. Environmental effects--HD 112-4-IR range..... | 75 |
| 81. Environmental effects--HD 112-5-UV-visible range..... | 75 |
| 82. Environmental effects--SL Spectrogard-UV-visible range..... | 76 |
| 83. Environmental effects--SL Spectrogard-NIR range..... | 76 |
| 84. Environmental effects--AF argon-UV-visible range..... | 77 |
| 85. Environmental effects--AF anti-red-UV-visible range..... | 77 |
| 86. Environmental effects--AF multiband-UV-visible range..... | 78 |
| 87. Environmental effects--AF multiband-NIR range..... | 78 |
| 88. Environmental effects--AF neodymium-NIR range..... | 79 |
| 89. Environmental effects--AF neodymium-UV-visible range..... | 79 |
| 90. Environmental effects--AF spectacle goggle-UV-visible range..... | 80 |
| 91. Environmental effects--AF spectacle goggle-NIR range..... | 80 |
| 92. Environmental effects--AF visible spectacle-IR range..... | 81 |
| 93. Environmental effects--AF IR-1-UV-visible range..... | 81 |
| 94. Environmental effects--AF IR-1-NIR range..... | 82 |
| 95. Environmental effects--AF IR-1-IR range..... | 82 |
| 96. Environmental effects--AF IR-2-UV-visible range..... | 83 |
| 97. Environmental effects--AF IR-2-NIR range..... | 83 |
| 98. Environmental effects--AF IR-2-IR range..... | 84 |
| 99. Environmental effects--AF IR-3-UV-visible range..... | 84 |
| 100. Environmental effects--AF IR-3-NIR range..... | 85 |
| 101. Environmental effects--AF IR-3-IR range..... | 85 |
| 102. Environmental effects--Rate of degradation for GO LGA..... | 86 |
| 103. Environmental effects--Rate of degradation for GO LGA..... | 86 |
| 104. Environmental effects--Rate of degradation for GO LGS-A..... | 87 |
| 105. Environmental effects--Rate of degradation for GO LGS-A..... | 87 |
| 106. Environmental effects--Rate of degradation for GO LGU-HN..... | 88 |
| 107. Environmental effects--Rate of degradation for GO LGU-HN..... | 88 |
| 108. Environmental effects--Rate of degradation for AF argon..... | 89 |
| 109. Environmental effects--Rate of degradation for AF argon..... | 89 |
| 110. CO ₂ damage threshold results on AO 680 eyewear..... | 90 |
| 111. CO ₂ damage threshold results on FS AL-1060-9 eyewear..... | 90 |
| 112. CO ₂ damage threshold results on AF IR-1..... | 91 |
| 113. Argon laser beam profile: Normalized intensity vs position..... | 92 |
| 114. Argon damage threshold results on FS AL-515-7..... | 93 |
| 115. Argon damage threshold results on AF spectacle goggles..... | 93 |
| 116. Argon damage threshold results on AO window laminate..... | 94 |
| 117. Argon damage threshold results on SL Spectrogard..... | 94 |
| 118. Normalized intensity vs position of the ruby beam scan for the damage and irreversible transmittance experiments..... | 95 |
| 119. Damage threshold power density vs absorption coefficient for typical bulk absorbers..... | 96 |
| 120. Ruby damage threshold results on AF anti-red..... | 97 |
| 121. Ruby damage threshold results on BL 5W3756..... | 97 |
| 122. Ruby damage threshold results on AO 588..... | 98 |
| 123. Ruby damage threshold results on GO LGA..... | 98 |
| 124. Reversible transmittance changes of AF anti-red eye protector..... | 99 |
| 125. Reversible transmittance changes of eye protectors AO 586 and GO R-7448-1 sideshields..... | 100 |
| 126. Laser beam intensity profile for reversible transmittance experiment..... | 101 |

CONTENTS (Continued)

| | <u>Page</u> |
|--|-------------|
| 127. Spectrolab plastic frames used for fume analysis testing..... | 102 |
| 128. GO LGS-NN sideshield used for fume analysis testing..... | 102 |
| 129. AF IR-1 lens used for fume analysis testing..... | 103 |
| 130. Impact resistance test results on HD 112-1..... | 104 |
| 131. Impact resistance test results on SL Spectrogard..... | 104 |
| 132. Impact resistance test results on AF IR-2..... | 105 |

LIST OF TABLES

Table

| | |
|--|-----|
| 1. Laser-protection eyewear used in study (lenses)..... | 106 |
| 2. Laser-protection eyewear used in study (frames)..... | 107 |
| 3. Dimensional standard compliance--ANSI Z87.1..... | 108 |
| 4. Baseline optical quality measurements..... | 109 |
| 5. Compliance with refractive and prismatic standards-ANSI Z87.1..... | 114 |
| 6. Qualitative shading assessment--ANSI Z87.1..... | 115 |
| 7. Qualitative assessment of samples exposed in environmental chambers..... | 116 |
| 8. CO ₂ damage threshold (visible) results..... | 118 |
| 9. Damage thresholds for argon exposures..... | 119 |
| 10. Argon exposures burn-through data..... | 120 |
| 11. Ruby laser eyewear protectors: power density required for damage..... | 121 |
| 12. Ruby laser eyewear protectors: irreversible transmittance change..... | 122 |
| 13. Reversible bleaching results..... | 123 |
| 14. Test parameters for fume analysis..... | 124 |
| 15. Results of fume analyses in percent of total gas collected from vaporized samples..... | 125 |
| 16. Impact resistance test results--ANSI Z87.1..... | 129 |

EVALUATION OF LASER-PROTECTION EYEWEAR

INTRODUCTION

Since the introduction of the first laser into the U.S. Air Force inventory, the U.S. Air Force has been concerned about potential eye hazards (12) and the proper selection and effectiveness of laser protection eyewear. Many different types of laser eyewear available either commercially or developed specifically for the U.S. Air Force have been evaluated in an attempt to protect USAF personnel (6, 8, 11). The results obtained from these efforts led to the development in 1974 by the USAF School of Aerospace Medicine (USAFSAM) of a comprehensive program for testing the reliability and effectiveness of laser-protection eyewear. The eyewear selected for the program was based on a survey conducted by USAFSAM and includes both USAF-developed visors and lenses and commercially available eyewear in common use by DOD personnel.

In February 1975, the USAFSAM and the Bureau of Radiological Health (BRH) signed an Interagency Agreement (IAG) No. 224-75-6002 under which USAFSAM in this testing program would include 20 additional types of laser-protection eyewear available to the general public. The basis for this agreement was that duplication of effort would be eliminated and a saving in money would be accomplished. BRH agreed to provide funding for the procurement of the additional eyewear and USAFSAM would perform optical quality tests under nonstress and stress conditions and present a final report.

This final report lists the tests performed, techniques employed, and summary of the results obtained from the evaluation of 60 different types of laser-protection eyewear materials. The 60 materials include: 41 commercially available lenses, 8 representative eyewear frames with dye materials added, 2 eyewear frames made of an opaque absorbent material, and 9 USAF-developed visors and lenses. The lenses and frames are identified by manufacturer and catalog number in Tables 1 and 2.

Two interim reports (9, 10) and a journal article (14) have been published pertaining to this work.

EYEWEAR CHARACTERISTICS

The purpose of laser-protection eyewear is to absorb or reflect the incident laser energy before it can enter the eye. This is generally accomplished by using either glass or filter materials (containing an absorptive organic dye) alone or in combination with dichroic coatings deposited on the filter material. The material is then shaped into a lens or a rectangular filter plate and used with an appropriate frame.

Frames can be made of rubber or plastic (soft or hard) and can contain an organic dye which offers attenuation to laser radiation or they can be opaque.

Design Parameters

At present the parameters used to describe the utility and effectiveness of a laser eye protector are its optical density (OD) at a specified laser wavelength (λ) and its luminous transmittance (Y). These terms are defined as follows:

$$OD(\lambda) = \log_{10} \frac{1}{T(\lambda)} = -\log_{10} T(\lambda) \quad (1)$$

$$Y = \frac{\int S(\lambda) E(\lambda) T(\lambda) d\lambda}{\int S(\lambda) E(\lambda) d\lambda} \quad (2)$$

in which

$T(\lambda)$ is the filter transmission-at a given wavelength (λ)

$S(\lambda)$ is the spectral irradiance of the illuminating light source (W/cm^2-nm), at a given wavelength (λ)

$E(\lambda)$ is the spectral sensitivity function of the eye as defined by the Commission Internationale de l'Eclairage (CIE) at a given wavelength (λ)

According to this definition, the luminous transmittance of a filter in an area illuminated by specified light source is the ratio of the apparent brightness of a white diffusing surface as seen through the filter to the apparent brightness of that same surface as seen with the unaided eye. Qualitatively, the luminous transmittance is a direct measure of the ability of a person to see through the filter in a given background light.

The human eye has different detection thresholds for light depending on wavelength and is limited to a well-defined spectrum. This spectrum has a spectral shift dependent on background light. Photopic or day vision refers to a light-adapted eye while scotopic or night vision refers to a dark-adapted eye. The relative spectral luminous efficiency of the eye (13) is presented in Figure 1. By comparing the transmission of a lens to the luminous efficiency of the human eye as in Equation 2, the luminous transmittance or visible light transmission efficiency of the lens is calculated.

The initial design philosophy for laser eye protection emphasized maximizing the OD at the laser wavelengths for which the device was designed, often at the price of having to accept a low luminous transmittance. Other considerations have now, however, come into the design picture.

The low luminous transmission of some commercial goggles has made them unacceptable for use in areas with limited background illumination,

and undesirable even in areas with high illumination. For any filter having absorption bands in the visible spectrum, increasing the OD of these absorption bands will decrease the luminous transmission of the filter. Conversely, the need for a high luminous transmission in the eye protectors for some laser system applications has necessitated a corresponding decrease in the OD at the laser wavelength in these devices. This need to balance luminous transmission against OD has become a major difficulty in the designing of suitable eye protectors.

Laser Beam Visibility

One of the advantages of using a laser that operates in the visible region of the spectrum is that the output can be seen. People who have worked with invisible infrared lasers can appreciate this advantage. In fact, low-powered visible lasers are generally used to assist in the alignment of infrared laser systems. This advantage of visible lasers is eliminated, however, if the safety goggles used have such high OD at the laser wavelength that they prevent viewing of the beam. This difficulty could lead to the undesirable practice of personnel taking off their safety glasses to see the beam. Therefore, a design goal is to have eye protection that has a sufficient OD to protect at the desired laser wavelength, but not enough to render the wavelength invisible. In this way, the laser beam may be viewed and used in safety.

Filter Breakdown

To insure eye safety, many of the commercial protector manufacturers have taken the approach of using high OD at some laser wavelengths; specified ODs greater than 10 are common. This approach does not consider the dependence of OD upon the beam characteristics (diameter, shape, pulse duration) of incident energy levels. However, prior studies have indicated the presence of reversible bleaching which is defined as a reduction in absorbance of a filter material which is transient in nature and occurs only as a beam of high irradiance light passes through the filter. Blumenthal and Mikula (6) have tested some protectors with densities less than 4.0 OD. Although their densitometer could not detect transmittance changes (bleaching), at low intensities, one sample (light blue anti-red PMMA visor) reversibly bleached to 22% of its original OD when exposed to 25 MW/cm². Consequently, this protector is not recommended for use with Q-switched lasers.

It is also a well-established fact that if the energy deposition is increased, structural damage will occur (6, 8). Two damage thresholds can be defined as follows: (a) a minimal structural damage threshold which is that level at which damage is first visible to the unaided eye; and (b) a macroscopic or catastrophic change which occurs at the energy level required to burn through or crack the material.

Irreversible transmittance change (bleaching), the state in which a change in OD occurs but is not transient, was also investigated. Irreversible transmittance is assumed to be a change in absorbance of the

dye but can occur in conjunction with a molecular or microscopic structural change in the lens material. The existence of irreversible transmittance change in samples exposed to constant light over a long period of time is well established. However, this effort attempted to create this change in a short time period at irradiance levels just below visible damage thresholds.

Style of Protectors

A survey of laser eyewear currently in use in the U.S. Air Force established that most eyewear can be divided into two groups: commercially available eyewear and USAF aircrew eyewear. Figures 2-7 are of typical commercial eyewear and Figures 8 and 9 are of special-purpose USAF aircrew eyewear. (See references 8 and 11 for information on eyewear.)

Spectacles with Side Shields (Fig. 2)

This device is similar to conventional spectacles, but contains opaque or dyed plastic side eyeshields to protect the eye from oblique exposure to laser radiation.

Flexible Goggles with Glass Lenses (Fig. 3)

This is a broad band device similar to welder's or chippers goggles and has two types of glass filters which are separated by a multilayer reflective coating.

Headrest Flexible Goggles (Fig. 4)

This device consists of a frame attached to the head by an adjustable band. Spring bar attachments connecting the frame to the band provide sufficient tension so that the goggle frame remains sealed on the face. The glass filter plate is made up of absorptive material that provides protection over the specified wavelength regions.

Coverall-type Flexible Vinyl Goggles (Fig. 5)

This device is similar to the headrest flexible goggles but uses an adjustable elastic headband. The device usually contains two plates. The first is an absorptive-type filter plate or a dichroic-coated filter plate, and the second is a clear plastic plate (used with an absorptive filter plate) or an absorptive filter plate (used with the dichroic-coated). These plates are separated by an air space to minimize optical interference and fogging.

Full-view Soft Vinyl Goggles (Fig. 6)

This device generally consists of a plastic frame containing a plastic, replaceable absorptive lens.

Full-view Hard Plastic Spectacles with Side Shields (Fig. 7)

This device consists of a one-piece dyed plastic spectacles with side shields.

Air Force Visor (Fig. 8)

This device is made of absorptive plastic material molded into a visor which is attached to a standard aircrew helmet.

Air Force Aircrew Spectacles (Fig. 9)

This is a standard Air Force aircrew spectacle frame fitted with lenses made of laser protective material (glass or plastic).

TESTING METHODOLOGY

Introduction

An overview of the original USAFSAM testing program methodology is described in SAM-TR-76-19 (9). This report presents the requirements for evaluating the eyewear, basic testing methods including instrumentation for performing these tests, and a discussion of testing methods. The basic methodology is presented in this report but will not be reproduced in its entirety in this section. However, during the development of these test procedures over a 3-year period, refinements have been made to this program to obtain more accurate and precise data. The second interim report, SAM-TR-76-45 (10), describes the results for the first 3-month period in the colorfastness (environmental effects) tests where moderate to severe changes in optical density, haze, and luminous transmittance were observed. This effort destroyed eyewear samples sooner than anticipated and led to a shortened and revised environmental effects program of 2,000 hours with scheduled testing at predetermined times.

The major tests performed on these 60 different samples can be divided into two broad categories: optical quality under nonstress conditions, and optical quality under stress conditions. The nonstress tests were designed to evaluate the optical distortion and spectral transmission characteristics for different types of eyewear and included: (a) measurement of thickness, width, and length; (b) determination of spectral transmission by spectrophotometry; (c) determination of OD by laser illumination methods; (d) measurement of haze and refractive and prismatic effects; and (e) calculation of luminous transmittance.

Optical quality under stress conditions was measured to test samples under thermal, illumination, and mechanical stress conditions because manufacturers do not provide this information. These tests included: (a) environmental effects--spectral and physical; (b) shelf-life testing--spectral and physical; (c) laser-induced visible damage

threshold and irreversible transmittance changes; (d) reversible transmittance changes; (e) fume analysis; and (f) impact resistance studies. A brief description of each test and changes from the original methodology of SAM-TR-76-19 is presented in the following sections. These tests parallel the requirements established under the Interagency Agreement. Power and energy measurement instrumentation used in the following experiments were compared against BRH transfer instruments, Korad Thermopile Model 100, and Keithley Multimeter Model 160B, which were calibrated against a National Bureau of Standards secondary standard source.

Optical Quality Under Nonstress Conditions

Dimension Standards

A review of ANSI Standards Z80.1-1972, Z87.1-1968, and Z136.1-1976 (2, 3, 4) establishes the need for conformance to standards concerning optical qualities and dimensions. All samples were inspected upon receipt and checked that surfaces were polished and free from striae, waves, or other defects which would impair their optical quality. All eyewear was then classified and appropriate standards concerning dimensions checked. The three classifications and applicable section from ANSI Z87.1 are (a) filter plates, (b) plastic or glass lens in rigid frames, and (c) plastic lens in flexible goggles. All measurements were done with a micrometer accurate to one ten-thousandth and a caliper accurate to one one-thousandth of an inch.

Spectrophotometry

Transmission curves (transmission vs. wavelength) and absorbance (optical density) values at discrete wavelengths were measured using either a Beckman Model MVII or a Beckman Model IR-9 spectrophotometer, depending on the spectrum of interest, ultraviolet (UV), visible (VIS), or infrared (IR). The instrument characteristics are listed as follows:

| <u>Parameters</u> | <u>MVII</u> | <u>IR-9</u> |
|--|-------------------------------------|----------------------------------|
| Range (nanometers, nm) | UV-200 to 800 nm NIR-800-3000 nm | 2500 to 25,000 nm |
| Transmission (%) | 0-10% or 0-100% | 0-10% or 0-100% |
| Absorbance (OD) | 0-3 OD | 0-3 OD |
| Scan Rate (wave number or wavelength/time, $\text{cm}^{-1}/\text{min}$ or nm/sec) | 2 nm/sec | $200 \text{ cm}^{-1}/\text{min}$ |

The Beckman MVII has a photometric accuracy of 1% for the UV-VIS and NIR ranges and a resolution of better than 0.05 nm and 0.3 nm, respectively. The Beckman IR-9 has a transmission accuracy of 1.0% absolute and a resolution of 0.25 cm^{-1} at 923 cm^{-1} .

Luminous Transmittance

The spectrophotometry transmission data from the visible (200-800 nm) range of the Beckman MVII is digitized using a Hewlett-Packard 9820 calculator equipped with a plotting board and digitizer. The luminous transmittance (Y) of the eyewear samples was determined from the digitized data using a program designed to compute Y from Eqn (2) on the Hewlett-Packard 9820 calculator.

ANSI standards for luminous transmittance cannot be directly applied to laser eyewear (14). According to ANSI Z87.1, "Visible Transmittance, Plastic Windows," clear windows shall have a luminous transmittance of 85% and colored windows, the following:

| <u>Shade</u> | <u>% Transmittance</u> |
|--------------|------------------------|
| Light | 50 ± 7 |
| Medium | 23 ± 6 |
| Dark | 14 ± 6 |

In contrast, proposed ISO standards quote 15% as the minimum luminous transmittance for standard filters. Therefore, it is reasonable to state that samples should have a luminous transmittance of at least 10% for the purposes of this study.

Laser Densitometer

Optical density measurements using laser illumination were made using a method developed in this laboratory (14). A pictorial schematic is shown in Figure 10. The uniqueness of this scheme is that the same beam is used for both reference beam and measurement beam.

By using an EMI type 9818 (S-20 surface) photomultiplier tube configured for short pulse measurement and a Molelectron Model DL 400 pulsed tunable dye laser, optical density measurements from 337.1 nm to 694.3 nm were obtained. These values were greater than 7.0 OD at 365 and 10.0 OD at the other wavelengths. The waveform is displayed on a Hewlett-Packard 184A storage oscilloscope with a 1805A dual channel amplifier and a 1825A time base plug-in. Approximately 20 pulses were accumulated for each measurement. Only samples rated at greater than 3 OD were measured using the laser densitometer since the spectrophotometers were capable of measurements up to 3.0 OD.

Because the experimental arrangement used the same beam for both reference and sample measurement laser instability, detector sensitivity and amplifier gain were removed as contributors to measurements errors. This meant the degree of error of OD measurements was dependent on the following factors: (a) readability of the pulse-heights displayed on the oscilloscope, and (b) the calibration of filters used with the system. Reading of pulse height from the scope contributed an average variation of about $\pm 2\%$ to each OD measurement. The neutral-density

filters were calibrated on a spectrophotometer with a variation of $\pm 1\%$. Therefore, the error in OD measurement was $\pm 2.2\%$.

Haze

A Gardner Model RG-1212 Pivotal Integrating Sphere Reflectometer with a PG-5500 Digital Photometric Unit was used to make haze measurements. The RG-1212 meets ASTM Test Method D-1003-61 for the measurement of haze and luminous transmission of transparent plastics. Measurements were made using both illuminant A and illuminant C used in haze measurements. ANSI Z87.1 standards were applied to all lenses and plates (14). The Gardner Hazemeter has an error of $\pm 5\%$.

Refractive and Prismatic Effects

A standard Bausch and Lomb (B&L) Vertometer Model 70 and a modified lensometer built by the USAFSAM Fabrication Branch were used to do refractive and prismatic effects measurements. The B&L vertometer has a range of -5.0 to +5.0 prism diopters in 0.25 diopter increments. The USAFSAM lensometer has a range of -0.5 to +0.5 prism diopters in 0.05 diopter increments. Each sample was first measured on the USAFSAM lensometer; then, sphere power (S), cylinder power (C), axis (X), and prism power (P) were recorded. The S and C values were combined to give a spherical equivalent power (S_{eq}) by the following equation:

$$S_{eq} = S + 1/2 C \quad (3)$$

Three measurements were made on each sample and averaged. If S_{eq} was >0.5 prism diopters, the measurements were made on the B&L vertometer. All samples were also tested to determine if they met ANSI Z87.1 standards for refractive power, in any meridian, and prismatic effect (2). ANSI Section 5.1.4.1.6 (6) was applied to all plates and Section 6.3.2.2 applied to all lenses.

Optical Quality Under Stress Conditions

Environmental Effects--Spectral and Physical

All lens and frame samples were subjected to environmental stress under controlled irradiation, sample temperature and humidity conditions. Two Atlas Model WR-600 weatherometers were used for this test. Both chambers maintained a sample temperature of $59^{\circ} \pm 1^{\circ} \text{C}$. One chamber maintained humidity at 20% or less and the other chamber was set at 75% or greater. Constant illumination in both chambers was provided by a Xenon arc lamp using an inner IR absorbing filter and an outer quartz filter. Luminance of 9100 foot-lamberts and illuminance of 7200 foot-candles was measured using a United Detector Technology Model 40-A power meter and the proper diffuser. The energy distribution in power per unit area per wavelength versus wavelength is in Figure 11, and was derived from manufacturer's specifications.

A revised exposure program was initiated due to the results of a pilot study reported in SAM-TR-76-45 (10). All samples were exposed for a total of 2000 chamber hours. During the first 400 hours of testing all samples were removed every 50 hours and visually inspected for signs of fading or deterioration. Random samples of each type were selected and transmission, lensometer, and haze measurements made. Thereafter, this was done every 100 hours for the second 400 exposure hours, and every 200 hours for the final 1200 exposure hours.

Shelf-Life Studies

For the shelf-life tests, six lenses of each sample were baselined and then placed in boxes for storage at room temperature (approximately 72°F) and 50% relative humidity. At the end of two years they were retested and compared with their original measured data.

Laser-Induced Damage

Damage threshold tests were performed under three sets of conditions: (a) samples providing protection in the region of 10600 nm were tested using a CO₂ cw laser, (b) samples providing protection at the argon laser wavelength of 514.5 nm were tested using an argon cw laser, and (c) samples providing protection at 694.3 nm were tested using a ruby Q-switched pulsed laser. Irreversible transmittance tests were performed using the ruby Q-switched laser.

CO₂ Exposures--The experimental apparatus is shown schematically in Figure 12. A Perkin Elmer Model 6200 CO₂ laser with 27 watt maximum output at 10.6 μ m wavelength was used. The gold-plated pop-up mirror protected the shutter from irradiation between exposures, and the radiation reflected from the mirror was monitored constantly and measured with a Coherent Laboratories (CRL) Model 201 power meter to give average laser power during an exposure cycle. Before each exposure, the laser output power measured by the CRL power meter was correlated with simultaneous measurements taken at the sample position with a Hadron Model 101 thermopile and digital voltmeter. Beam diameter was set at 7.5 mm by using an aperture. This was confirmed by a series of beam scans which established the beam to be Gaussian at all power levels. A Spectra Physics Model 55 HeNe laser was used to align the optical setup. Two important types of damage are of interest in this experiment. The first type was the threshold value at which visible damage occurs. Damage was defined as dimpling, increased opacity, stress cracks, melting, or any other visible change. The second type was at what power levels and time exposures would complete burn-through occur. This phase was limited by laser output.

The experimental procedure was to set the shutter for an exposure time of 4.45 seconds for plastics and 9.2 seconds for glass samples. Samples were then exposed at increasing power levels until visible damage occurred. For complete burn-through, laser power was set to maximum output and the sample exposed until complete burn-through was

achieved or in the case of glass samples until the glass cracked, and in the case of combination plates until the plastic plate had melted. The exposure was terminated after 2 minutes if no damage had occurred.

Argon Exposures--The experimental apparatus for argon (514.5 nm) damage threshold testing is presented in Figure 13. A Spectra Physics Model 170 cw laser with output ranging from 0.6 to 10 watts at 514.5 nm was used. A filter stack was used to attenuate the power when so desired. Exposure times were controlled by an electronic shutter/timer system. In order to monitor the power at all times, the beam was split and a PIN photodiode used to measure the reference beam. Reference beam power levels were then calibrated against measurements made at the sample holder using a power meter. During exposures the power meter was placed 7.6 cm behind the sample holder and used to determine any change in the OD due to bleaching or burn-through. The difference in power readings taken at the sample holder and 7.6 cm in back was less than 1%.

The sample was placed at a convenient distance of 76.2 cm from the laser output aperture during testing. The beam was Gaussian and had a beam diameter of 1.8 mm at the $1/e^2$ power point. When it was necessary to attenuate the beam, only Inconel filters were used to avoid a lensing effect that was noticed when neutral-density filters were used.

Damage threshold in this test was defined as any structural damage (such as a blemish on glass or dimple on plastic) or a permanent change in the opacity of the material or dye. Complete burn-through in plastics or shattering in glass samples was also attempted.

The Spectra Physics Model 170 argon laser used had a built-in beam stabilizer making the output stability $\pm 0.5\%$ below 230 W/cm^2 and $\pm 10\%$ above that value. The symmetry of the beam and its output stability implied that image size estimation was accurate to within 10%. The meters used to measure power were accurate to within 5% at low power levels and 2% at high power levels.

Some variation was introduced in assessing the point at which damage occurs. Agreement between observers in judging damage was quite good for all exposures; therefore, the average variation from subjective damage evaluation was estimated to be $\pm 2.0\%$.

Ruby Exposures--An Apollo Model 5 ruby Q-switched laser and amplifier were used to determine the power density required for damaging the ruby eye protectors. The apparatus arrangement is shown in Figure 14. The laser provided a 16 nsec half-height duration pulse with output energy of approximately 10 joules. The power density illuminating the sample was varied by changing (a) calibrated neutral-density filters, and (b) the distance between the 50 cm focal-length lens and the sample. The beam was apertured to 2 cm and a power reference beam was split from the primary probe beam. Hadron models 100 and 101 thermopiles and a neutral-density filter stack were used to calibrate the beam splitter. The sample was normally located 42.2 cm from the lens. When additional power density was required, the distance between the lens and the sample was increased to 47.4 cm for geometric reduction of the image.

A sample was exposed to the estimated power density required for damage. The energy per pulse was monitored and the sample examined for damage. Then, depending on the results, the power density was either increased or decreased by changing the neutral-density filters in steps of 0.3 OD. A different exposure site on the sample was selected, and the procedure was repeated until the results (damage or no damage) were reversed. Then 0.1 OD increments were used to obtain a similar reversal.

The beam profile of the ruby laser was measured using the same arrangement in Figure 14 with the sample replaced by a 0.05 cm pinhole and a TRG Model 105B photodetector. The output of the detector was recorded with a Tektronix Model 519 oscilloscope. The pinhole was positioned at the beam center by exposing black Polaroid film with the laser pulse and moving the pinhole to the center of the film burns. The pinhole and detector were incrementally scanned through the beam center in steps of 0.64 mm and the response for each pulse was normalized with respect to the reference energy for that pulse.

Power density at the sample was calculated using the reference energy, the beam splitter calibration, the half-height pulse duration and the beam image diameter at the $1/e$ power point. The power density required to produce damage was determined from the geometric mean of the highest power density that did not produce damage and the lowest power density that did produce damage.

Irreversible Transmittance--In order to determine if ruby (694.3 nm) protectors were prone to irreversible transmittance changes, it was necessary to attempt to change dye absorbance without visibly changing lens structure. The experimental apparatus arrangement was the same as for the ruby damage threshold testing (Fig. 14). The experiment consisted of the following three-step procedure: (a) measure the sample OD using the laser densitometer; (b) expose the sample to approximately half the power density required for damage; and (c) remeasure the OD with the densitometer. The two measurements and the exposure were performed at a single predetermined site on each sample. The densitometer sample beam was slightly larger than the ruby exposure site. The samples were exposed to approximately 50% of the power density required for damage. After each ruby exposure, the sample was examined for possible damage.

Reversible Transmittance

The reversible transmittance experiment was conducted by using a Q-switched ruby laser with a pulse width of 16 nsec and the optical delay densitometry technique developed in this laboratory (14). A single detector measured both the light pulse transmitted through the sample and a reference pulse which was delayed 64 nsec.

The optical arrangement is shown in Figure 15. An Apollo Model 5 Q-switched pulse laser with a half-height pulse duration of 16 nsec and

a peak energy of 2.45 joules was used. This energy was attenuated with calibrated neutral-density filters to approximately 5% of the energy required for damage. The beam was then apertured to 2 cm before it was transmitted through the sample and a combination delayed reference and trigger beam was obtained from a beam splitter. The sample beam passed on through a 50 cm focal-length lens which focused the beam beyond the sample. Neutral-density filter stacks were located an equal distance from the beam waist. A light shroud was needed to assure that no stray light (from ambient room light, beam reflections and flash lamps) entered the fiber optics. The shroud also formed a 3-cm aperture. A lens (focal length 13 cm) focused the sample beam into the fiber optics which transported the light pulse to an RCA Model 7102 photomultiplier tube powered by a Fluke Model 415B high-voltage power supply. The combination delayed reference and trigger reflection beam obtained at the beam splitter had 3 functions. First, it provided a laser power reference; second, it triggered the oscilloscope; and third, it provided a delayed power reference pulse for the OD measurement. A closed steel cabinet surrounded the detector-oscilloscope assembly in order to shield the measurement equipment from electromagnetic noise.

The optical density at a given laser pulse intensity was determined by the method given in reference 14. An optical-density measurement range of 11.0 OD was attained. Samples were exposed to a maximum power density approaching 1% of the visible damage threshold.

The OD was calculated by using the difference of the value of the standardized filters removed (f_r) and the \log_{10} of the ratio of the sample pulse amplitude (A_p) to the reference pulse amplitude (A_r), i.e.,

$$OD = f_r = \log_{10}(A_p/A_r) \quad (4)$$

The beam-profile measurement apparatus is shown in Figure 16. The profile measurement procedure is similar to that for the ruby damage experiment.

Fume Analysis

Fume analysis testing was performed using the basic experimental setup described in CO₂ exposure tests. A vacuum gas collection probe was used to collect the fumes (Fig. 17). Samples were grouped according to type material (cellulose, propinate, glass, etc.) and color of dye (orange, blue, clear, etc.). Ten representative samples were then chosen and tested. Laser power output was set to a maximum (nominal 27 watts) and the sample irradiated until burn-through occurred. The fumes were then collected at a rate of 1 liter per minute for approximately 30 sec. The gas samples were then analyzed by the Crew Environments Branch, Crew Technology Division, USAFSAM, using a mass spectrometer.

Impact Resistance

All lenses were tested for impact-resistance qualities using ANSI Z87.1 (2). Samples were tested by one or both of the following tests. The first test consisted of a 7/8-in. (2.22 cm) steel ball freely dropped from a height of 50-in. (127 cm). The second test consisted of a 5/8 in. (1.588 cm) steel ball freely dropped from a height of 39.3 in. (100 cm). All lenses were placed on the recommended lens support described in ANSI Z87.1 for each type lens.

RESULTS AND DISCUSSION

Optical Quality Under Nonstress Conditions

Dimensions

Upon receipt, all eyewear samples were inspected and accepted only if their surfaces were found to be well polished and free from striae, waves, and any other defects which would impair their optical quality. No eyewear was rejected on this basis. However, several sideshields from the GO HN-7448-1 samples had uneven dye distribution. A difference in shade was also noted on some GO LGS-R lenses, but they passed the other tests and were therefore acceptable. Most filter plates, plastic lenses from goggles, and the frames from rigid spectacles had the OD clearly stamped with the corresponding wavelength; however, there was no uniform method of labeling. The general appearance of the laser eyewear tested would have to be rated acceptable overall.

The dimensions of all samples were then measured and compared to applicable ANSI standards. See Table 3 for results. The first class of eyewear filter plates was subdivided into two groups: (a) combination plates--one or more layers with a frame, and (b) single-layer plates. All combination plates were found to exceed the maximum allowable thickness of 0.150 in. (.38 cm). American Optical (AO), Bausch and Lomb (B&L), and Hadron (Hd) manufactured the combination plates tested. Several single-layer plastic filter plates from Glendale Optical (GO) LGU series failed to meet the minimum required length of 4.25 in. (10.8 cm) \pm 0.03. Fish-Schurmann's (FS) AL-633-5 and AL-1060-9 glass single-layer plates also exceeded the maximum thickness. In the second class, separate lenses from spectacles FS, AO, and Spectro Lab (SL) all exceeded the maximum thickness of 0.150 in. (.38 cm), while GO lenses did not meet the minimum thickness of 0.118 in. (.30 cm). All lenses from the third class, single lens for flexible goggles, exceeded the minimum thickness of 0.050 in. (.13 cm).

As a general rule, plastic lenses were found to vary \pm 2.5% in thickness on any given lens and \pm 5% for any given model. Glass lenses were found to vary \pm 1% on any given lens and \pm 2% for any given model. The variation among combination plates was found to be \pm 3% for any given plate and \pm 6% for any given model.

Spectrophotometry

Transmission measurements were performed for three ranges: (a) UV-Visible, 200-800 nm; (b) Near Infrared, 800-3000 nm; and (c) Infrared, 2500-25,000 nm. A Beckman Model MVII spectrophotometer was used for the first two ranges and a Beckman Model IR-9 spectrophotometer for the third. Transmission data were not measured to compare against any standard but were intended to serve as a baseline which could be used to detect any spectral changes while the samples were undergoing tests such as shelf-life and environmental effects. The data are plotted in Figures 18 to 101. A solid line represents an average value of 18 samples of each type of eyewear. Of these 18 samples, 6 were used for shelf-life testing, and 12 for the environmental effects part of the program.

Data are plotted as transmission (0-100%) versus wavelength, in nanometers. The manufacturer and model number of the samples are listed at the top of the graph. There is a separate plot for each range over which a sample was measured. The IR-9 plots go to only 5000 nm since all samples measured from 5000-25,000 nm had less than 1% transmission.

Optical Density

Laser optical-density measurements were performed on 41 different eyewear types. Measurements were limited to 7.0 OD at 3.65 nm, 8.0 OD at 1060 nm, and 10.0 OD at other wavelengths. The other wavelengths used were 458, 514.5, 530, 632.8, and 694.3 nm. The 1060 nm OD data were measured using a Korad neodymium glass pulsed laser with the same general optical experimental setup and procedure used with the Molelectron dye laser (Fig. 10). No OD measurements were made at 332 nm and 337.1 nm because the samples measured were rated within the 3 OD range of the Beckman Model MVII. No laser was available to do OD measurements at 840 nm or any other IR wavelengths with the exception of 1060 nm. Therefore, these wavelengths could only be checked with the spectrophotometers which had their absorbance range expanded to 4 OD by insertion of neutral-density filters in the reference beam path. Eyewear types, with manufacturers' specified OD, wavelengths of protection, and the corresponding measured values are listed in Table 4.

The OD values listed in Table 4 are an average of a minimum of 12 samples measured for each type eyewear at the specified wavelength. Of the 41 protectors evaluated, 8 failed to exceed or meet the rated OD within 10%. It should be noted that the helium neon wavelength of 632.8 nm comprises 4 of these 8 values. Nineteen other measurements were made at equipment limits, but manufacturer's specifications were higher; therefore no conclusion could be reached on these ratings. These protectors and the wavelengths of interest are listed on the following page.

| <u>Protector</u> | <u>Rated OD at (nm)</u> | <u>Measured OD at (nm)</u> |
|------------------|-----------------------------|--------------------------------|
| AO 599 | 14.7 @ 455 | 9.3 @ 455 |
| AO 698 | 8.5 @ 530 | 7.5 @ 530 |
| BL 5W3754 | 17 @ 458 | 9.9 @ 458 |
| FS AL-633-5 | 5 @ 632.8 | 3.8 @ 632.8 |
| GO LGS-HN | 6 @ 632.8 | 5.3 @ 632.8 |
| GO HN-7448-1 | 6 @ 632.8 | 5.3 @ 632.8 |
| SL Spectrogard | 7 @ 632.8 | 6.1 @ 632.8 |
| AF Argon | 5 @ 14.5 | 3.8 @ 514.5 |

Haze

ANSI Z87.1 lists a haze standard of no more than 6% for all occupational eyewear for illuminant A and illuminant C, CIE. All samples met this standard. The results are presented in Table 4.

Refractive and Prismatic Effects

In accordance with ANSI standards, filter plates and lenses shall have a prismatic effect of $<1/8$ prism diopters. In addition, lenses shall have a refractive effect of $<1/16$ diopter in any meridian. The compliance results are tabulated in Table 5. A spherical equivalent was also calculated as a simple means of evaluating lenses undergoing testing for any refractive or prismatic effect changes. See Table 4 for spherical equivalent data. Results indicate that GO 7448 series lenses and LGU series filter plates failed to meet ANSI standards. An analysis of these samples revealed GO 7448 series lenses had exceeded the refractive effect standard of not more than ± 0.06 diopters in both principal meridians (90° and 180°). However, they did not exceed the prismatic effect standard of 0.12 prism diopters which is the difference of the two principal meridian refractive effect values.

The GO LGU series filter plates failed the refractive effect standard in the horizontal meridian (180°). Consequently, the prismatic effect standard was also exceeded. The only glass lenses that did not meet ANSI standards were AO 586, SL Spectrogard, and AF IR-3.

Luminous Transmittance

Using the transmission curves from the 200-800 nm range, luminous transmittance was calculated with a Hewlett-Packard 9820 calculator using the human photopic and scotopic visual response curves from Figure 1. The manufacturer's specification, when available, and the measured photopic and scotopic values are given in Table 4. Of the 36 samples measured, only 16 photopic and 20 scotopic values met the quoted luminous transmittance specifications (44% and 56%, respectively).

Another comparison was made with ANSI Z87.1. All 50 lenses were qualitatively inspected and labeled as being of a clear, light, medium, or dark shade (Table 6). Then, using ANSI standards, 36 photopic and 28 scotopic measurements out of 50 samples passed photopic and scotopic LT (72% and 56%, respectively). Of 15 samples classified as being dark, 9 failed photopic LT and 10 failed scotopic LT values. This approach implied that although a large number of eyewear protectors do not meet manufacturers' specifications, many do meet ANSI Z87.1 standards for colored plastics. Also, many dark eyewear do not meet ANSI standards. However, if ISO guidelines are followed, they would be classified as special protectors and would not be required to meet the IOS LT requirements of 15%.

Optical Quality Under Stress Conditions

Environmental Effects

Single-layer plastic lenses or sideshields with organic dyes were the most susceptible to damage under conditions of low (<20%, dry sample) and high (>75%, wet sample) humidity. Generally, most plastic samples faded or bleached with the exception of AO window laminate, G0 LGS-NDGA, and G0 LGS-R sideshields which darkened. Striae or parallel streaks on the surface were present on both wet and dry samples but were more pronounced and occurred more frequently on wet samples. Sideshields made of hard plastic for the most part become brittle while rubber sideshields lost their smooth surface and appeared sticky to the touch. Several sideshield samples which had uneven dye distributions (spotched) faded and bleached unevenly. Combination filter plates consisting of a frame, an absorbing or coated front glass filter plate, and a back plastic plate separated by an air gap were affected mostly by high humidity. No damage was detected on any glass plates. The plastic plates suffered surface deterioration speckling (striae), whenever moisture seeped into the air gap. This deterioration occurred on the inside of the plastic plate and only to wet samples. Those samples having a dichroic coating suffered deterioration and cracking of the coating on wet samples and some discoloration on dry samples.

Glass samples did not undergo any changes in color or structural deterioration under any conditions. Table 7 presents a qualitative assessment of the resulting physical changes.

The average transmission curves of all samples before and after exposure are shown in Figures 18 to 101. Transmission (0-100%) versus wavelength (nm) is plotted on each graph. The solid curve represents the average transmission of the samples before exposure. The dotted or short dashed curve represents the average transmission of samples exposed for 2000 hours under low humidity conditions, while the long dashed curve represents the average transmission of samples exposed for 2000 hours under high humidity conditions. Any overlapping curves are represented by a dotted and dashed line. Eyewear type, the exposure

conditions, and pre- and postexposure photopic and scotopic luminous transmittance are given on each graph. A random sample of each model eyewear from both chambers was evaluated every 50 hours for the first 400 hours, every 100 hours for the second 400 hours, and every 200 hours for the final 1200 hours. Spectral transmission curves, haze measurements and, when applicable, laser OD measurements were taken. Curves depicting the rate and amount of degradation for each of four different eyewear types showing significant deterioration under both high and low humidity are presented in Figures 102-109. Most samples differed less than 10% from the original transmission curve under both low and high humidity conditions.

Shelf-Life Study

After 2 years of storage under controlled conditions the spectral parameters of the stored samples were remeasured and compared to their baseline data.

The parameters measured were optical density, transmission, luminous transmittance, haze and spherical equivalence. Because there were no significant differences (changes < 5%) in most cases, the data are not repeated. The data presented in Table 4 are essentially the same data collected after 2 years. The only physical change noted was some bleaching of the dye of G0 LGB eyewear which was stored inside a plastic bag in a box. All other samples showed no signs of deterioration.

CO₂ Exposures

CO₂ damage threshold results are contained in Table 8. Four plastic and four glass samples were tested. A damage threshold in terms of integrated power (joules) for a 4.45-sec exposure was established for each plastic sample. These samples were also irradiated at maximum available laser power until burn-through was achieved. Because of their durability, glass samples were irradiated at maximum power until a blemish appeared and the exposure was terminated when the lens cracked, exploded, or other macroscopic damage occurred.

Two of the plastic samples (A0 Tourgard and AF Visible Spectacle) were not laser-protection eyewear but clear safety glasses; however, they had higher damage thresholds than the laser-protection eyewear with dye absorbers (8.84 and 13.65 joules, respectively, against 5.88 for AF IR-1 and 6.46 joules for AF Nd). The two clear samples required total energy or burn-through approximately one-half that of A0 Tourgard. The glass sample damage thresholds were at least one and a half orders of magnitude greater than plastic samples. For two samples, FS AL-1060-9 and HD 112-4, no damage threshold was achieved. Only macroscopic damage (cracking) was achieved. Representative damage results are presented in Figures 110-112.

Argon Exposures

The CW damage threshold results for 15 samples at 514.5 nm are presented in Table 9. This table includes the damage threshold (DT), a brief description of the type of damage and the absorption coefficients (α) where α is

$$\alpha(\text{cm}^{-1}) = \frac{\text{OD} (\ln 10)}{\text{thickness (cm)}} \quad (5)$$

All DT's were determined for 1-second exposures. The beam profile for the damage experiment is shown in Figure 113. The $1/e^2$ power point diameter was 1.8 mm and had a Gaussian distribution. Different damage properties were observed among the three different materials tested--dichroic, glass, and plastic. No DT could be obtained for the dichroic sample (BL 5W3754) because of the available laser power output limitations. It is listed as greater than 286.9 W/cm² in Table 9. The five glass samples had DT's that ranged from 121.8 to 286.9 W/cm². Plastic samples had DT's that ranged from 5.8 to 17.7 W/cm². An analysis of damage threshold results indicated that dichroic materials had the highest DT while plastic samples had the lowest. Samples made of similar material required approximately equal power densities in order to produce damage.

A comparison of α 's and DT's points out that the lower the α the higher the DT. For example, AO 599 (a glass sample) when compared to GO LGB (a plastic sample) had a DT 50 times greater but an α one-third smaller. This relationship was generally true for most samples and implied that for optically dense material, the DT was significantly dependent upon α .

The second phase of this experiment was to determine what power density would be required to achieve 1-second burn-through (BT) on plastic lenses and macroscopic damage on glass eyewear. Results are in Table 10. One-second BT was achieved on four plastic samples (GO LGB, GO A-7448-1, AF Spectacle Goggle, and AF Multiband) with power densities ranging from 171.0 to 287.0 W/cm². Several plastic samples such as the GO A-7448-1 lens burst into flames short of the required testing time (1 second). GO LGU-A, AF Argon, and AO Window Laminate were irradiated at maximum available power output without achieving BT for 1 second. AO Window Laminate, a two-layer sheet, was exposed for 45 seconds with BT being achieved only on the first layer, making it the sturdiest of the plastic samples.

Glass eyewear were found to be extremely durable. AO 598, AO 599, and BL 5W3754 were irradiated at maximum available laser power with no damage or a slight blemish at most. FS AL-515-7 was the only glass sample on which macroscopic damage was achieved. It cracked in half at 55.0 W/cm²; however, this occurred after a 40-second exposure.

A comparison of DT and BT revealed that in order to achieve BT for 1 second, power density had to be at least one order of magnitude greater than the DT value, even for samples with low DT's. Glass samples were the most durable; however, plastic laminates showed promise of offering extremely good protection. Representative pictures of damage results are presented in Figures 114-117.

Ruby Exposures

The damage threshold results for 18 ruby eyewear samples at 694.3 nm are presented in Table 11. The table includes the damage threshold (DT), a brief description of the type of damage, and the absorption coefficients. Different damage properties were observed among the three different materials--glass, dichroic, and plastic. The DT for the eight glass samples ranged from 6.0 to 100 GW/cm². Sample AO 584 had a DT of 101 GW/cm² and sample FS AL-633-5 had a DT of 48.2 GW/cm², which were the two highest measurements. These were the only two samples made of Schott glass. The DT for the remaining 6 glass samples ranged from 5.8 to 8.26 GW/cm². The DT of the plastic samples ranged from 0.242 to 1.78 GW/cm². The dichroic coated materials had DT's that were approximately equal (0.182 to 0.373 GW/cm²). An analysis of ruby damage results indicates that glass samples required a higher power density to cause damage than dichroic samples. Samples made of similar material required approximately equal power density to produce damage. The beam profile for the damage experiment is shown in Figure 118. The 1/e power point diameter is 2.26 mm and the beam is assumed to be cylindrically symmetric for power density calculations.

Absorption coefficients are calculated as in Equation 5. The gap distances between layers in the multilayered samples are considered to be negligibly small. Absorption coefficients are not estimated for dichroic protectors. A plot of DT versus sample absorption coefficient (α) shows an exponential relationship between high DT and low absorption coefficient (Fig. 119). In other words sample GQ LGS-R sideshield had a relatively large absorption coefficient (151 cm⁻¹), and damaged at a relatively low power density (0.242 GW/cm²). In contrast, sample FS AL-633-5 had an absorption coefficient one-fourth as large as that of the other sample and required 200 times the power density for damage. An exponential curve was fit to the data points in Figure 118 by first transforming the exponential equation:

$$y = be^{m\alpha}, \quad (6)$$

in the following manner

$$\ln y = \ln(be^{m\alpha}) = \ln b + m\alpha. \quad (7)$$

The data were then transformed logarithmically and a least-square linear regression applied which fit the straight line plotted in Figure 118 to the data points. Equation 6 was then rewritten as follows:

$$PD = 12.2 e^{-(0.024\alpha)} \text{ (GW/cm}^2\text{)}. \quad (8)$$

PD is the threshold power density.

One can note that damage will result in samples with zero absorption coefficient at 12.2 GW/cm². This agrees with the damage power densities reported by Bass and Barrett (5) for plastics, glass, and fused quartz of 16.1, 14.4, and 24.0 GW/cm², respectively. Thus, for damage to optically dense material, as in this experiment, the damage threshold is strongly dependent upon the absorption coefficient. Representative pictures of typical damage are presented in Figures 120-123.

Irreversible Transmittance

Results for laser-induced irreversible transmittance changes are presented in Table 12. Eighteen samples ranging in OD from 4.0 to 9.3 were tested at power densities ranging from 32% to 70% of damage threshold. The percent changes in OD were from +4.0% to -5.6%. The sensitivity of the detector allowed measurements on samples of 9.3 OD or less. Irreversible changes in transmittance could not be detected if the sample OD was greater than 9.3. There were no visible indications, such as discoloration, of any changes in the protectors. The changes in OD were of the same magnitude as the laser densitometer measurement error (+2.2%), except for sample A0 586. For this sample, the 5.6% drop in OD following the ruby exposure exceeded the measurement error.

Reversible Transmittance

Reversible transmittance (bleaching) is a change, temporary in nature, in the absorbance of a dyed material induced by a pulse of high-energy irradiance. This change is a function of the irradiance with optical density decreasing as the intensity of the pulse increases.

Three of the 14 samples had a transmittance increase of more than 4% when radiated at 1% of the damage power density. Results from these samples are tabulated in Table 13 and plotted in Figures 124 and 125. Table 13 includes sample identification, ruby laser densitometer OD measurement, power density at the sample for the ruby laser densitometer measurement normalized to the damage power density, and percent change in OD. The most dramatic transmittance change occurred with the AF anti-red sample which reduced to 30% of its original OD. The original OD of samples G0 R-7448-1 sideshield and A0 584 lens reduced to 90% and 96%, respectively. The OD of the other samples failed to vary with power density by more than 3.2%. The three samples that demonstrated reversible transmittance changes were single layers of plastic. The

beam profile for the reversible transmittance is shown in Figure 126. The 1/e power point diameter was 5.7 mm.

Fume Analysis

A list of ten samples tested and the gas collection parameters are presented in Table 14. The fume analysis results are presented in Table 15 with compound classes and compounds listed as a percentage of the total gas collected. Five of the samples contained from 4.1% to 36.1% benzene listed as a suspected carcinogen by NIOSH (7). The other five contained from 39.6% to 52.6% propionic acid listed as a carcinogen by AFOSH (1). Eye and nose irritation was experienced during the testing which may be due to the aldehyde content (3.3% - 13.9%). The next most significant class of compounds identified were the olefins (13.5% - 63.7%). Representative pictures of typical vaporized areas are presented in Figures 127-129.

Impact Resistance

The results of drop ball testing of the materials are presented in Table 16. FS AL-633-5 eyewear came in both filter plate and lens configurations. Air Force visor materials were tested in a plastic sheet form and not in the visor configuration. Most plastic lenses with the exception of AF visor plastics passed the most stringent test (7/8-in. (2.22 cm) steel ball at a height of 50 in. (127 cm)). Combination filter plates and glass filter plates which failed the most stringent tests were retested with a 5/8-in. (1.588 cm) steel ball at a height of 39.3 in. (100 cm). A total of 10 lenses failed to pass either test. Representative pictures of typical damage results are presented in Figures 130-132.

CONCLUSIONS

The conclusions presented here are of a general nature and are intended to be applicable to eyewear according to construction, material, and spectral band of protection. Results on specific types of eyewear are presented in the Results section of this report. Conclusions pertaining to specific eyewear models can be inferred from the results.

Optical Quality Under Nonstress Conditions

The lenses of eyewear received were found to be of good appearance and were free from visible defects such as striae and bubbles. However, the dye distribution of several plastic sideshields was found to be uneven and unacceptable. Plastic lenses were found to vary $\pm 2.5\%$ in thickness for any given lens and $\pm 5\%$ for any model group. Filter plates and spectacles with separate lenses were generally found to exceed ANSI Z87.1-1968 standards for maximum thickness of 0.150 in. (.38 cm). Only

two out of six commercial manufacturers in this study gave a luminous transmittance specification for their eyewear. Eyewear labeling was found to be inconsistent on information given and method of labeling.

Optical density measurements of $10 \pm 2.2\%$ absorbance units were achieved for wavelengths in the 458 to 694.3 nm range, $7 \pm 2.2\%$ units at 365 nm, and $8 \pm 2.2\%$ units at 1060 nm. Most optical density measurements were found to be consistent with manufacturers' specifications; however, four different sample types designed to provide protection at 632.8 nm had measured OD's that were more than 10% below specifications. Of the eyewear having a luminous transmittance specification only 44% met it for photopic vision and 56% for scotopic vision. All eyewear met the ANSI Z87.1-1968 standard of no more than 6% haze. Concave plastic lens and full-view plastic filter plates tested did not meet ANSI Z87.1-1968 standards for refractive and prismatic effects.

Optical Quality Under Stress Conditions

Argon eyewear was found to be the most susceptible to sunlight and had a very fast deterioration rate when compared to other eyewear. Humidity causes the most environmental damage to plastic eyewear. A good seal is especially important on combination filter plates because humidity that is trapped in the air gap between plates causes rapid and severe deterioration to the plastic plate. Humidity also affects the amount of haze in plastic eyewear to the point where the ANSI standard of no more than 6% haze may be exceeded. Refractive and prismatic powers were not affected by humidity, temperature, or sunlight in the samples tested. No spectrophotometric or physical changes were noticed on glass eyewear or glass plates in the combination filter plate protectors during environmental effects testing. The same was true for samples tested for 2 years in the shelf-life phase of this program with the one exception of leaching in the GO LGB samples.

Glass eyewear have higher measured visible damage thresholds for ruby pulse and CO_2 CW exposures. Clear plastic safety glasses provided as much protection at 10.6 μm as plastic IR protectors containing absorbent dyes designed to attenuate laser beams. Schott glass IR protectors that were subjected to CO_2 CW exposures had no visible damage prior to shattering (exploding). A Bausch and Lomb (5W3754) dichroic coated protector had a higher measured damage threshold for CW argon exposures than the other samples tested. Power densities one order of magnitude greater than the measured damage threshold were required to achieve 1-second burn-through in the plastic argon eyewear that was tested. For absorptive ruby materials, the power density required for visible damage is systematically dependent upon the absorption coefficient.

Irreversible transmittance changes at 694.3 nm are not observed when ruby samples are exposed to one-half the measured damage threshold power density. Reversible transmittance changes at 694.3 nm were recorded in three of the ruby samples tested at 1% of the measured damage threshold. Five of ten materials vaporized with a CO_2 CW laser were

found to contain 4.1% to 46.1% benzene and 39.6% to 52.6% propionic acid, by weight, of the total gas collected. Benzene is listed as a suspected carcinogen by NIOSH (7) and propionic acid is on the known carcinogenic substance list of AFOSH (1). Twenty percent of the materials tested failed to meet ANSI Z87.1-1968 impact resistance standards.

RECOMMENDATIONS

A luminous transmittance standard incorporating the shading scheme of ANSI Z87.1-1968 or a similar method should be established for laser-protection eyewear. Luminous transmittance should be specified as being a scotopic vision or photopic vision value. An additional specification should be required of manufacturers. This specification should give the power density required to burn-through plastic, shatter glass, produce transmittance changes (reversible or irreversible), or other well-defined damage points. This should apply to both CW and pulsed lasers. Better humidity seals are needed on combination filter plates. Labeling of eyewear should be standardized and should include optical density, wavelength, and luminous transmittance and maximum irradiance levels.

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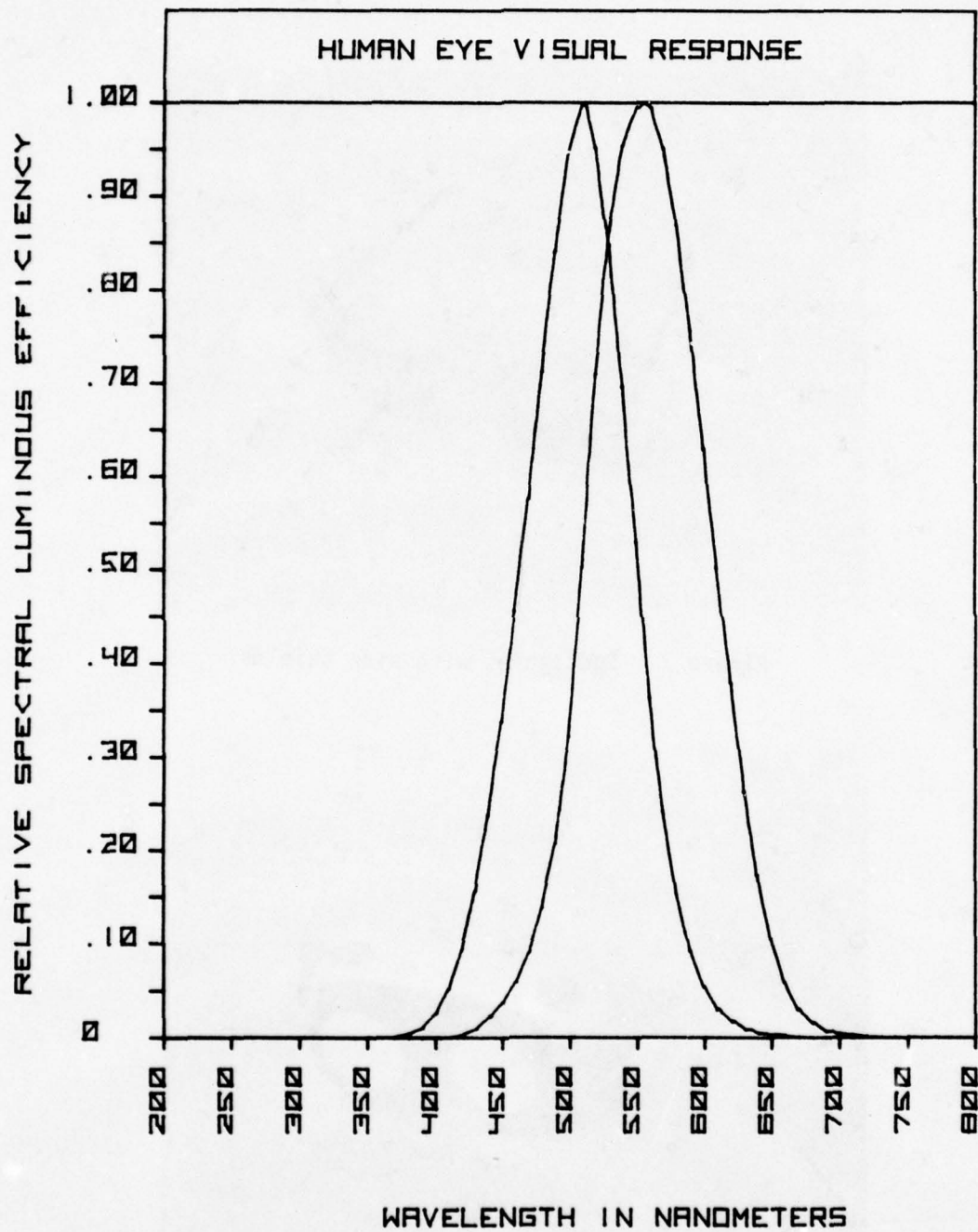


Figure 1. Relative spectral luminous efficiency of the human eye.

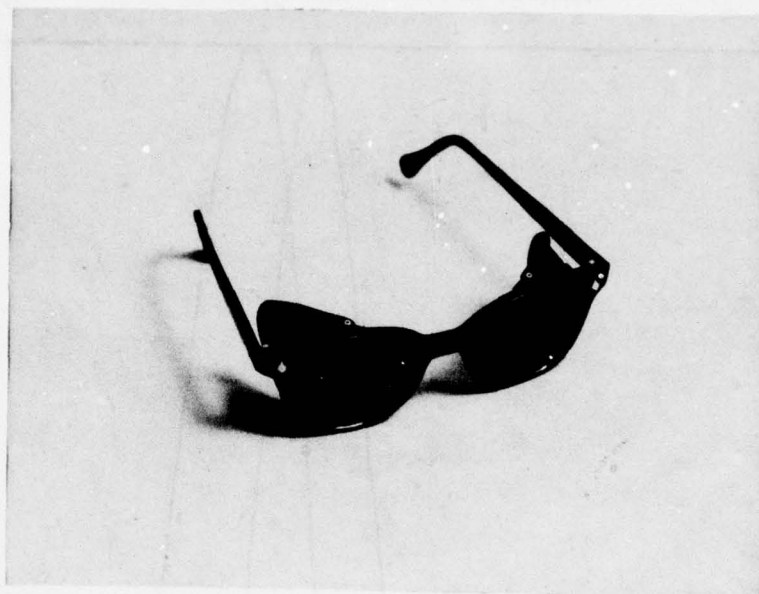


Figure 2. Spectacles with side shields.



Figure 3. Flexible goggles with glass lenses.

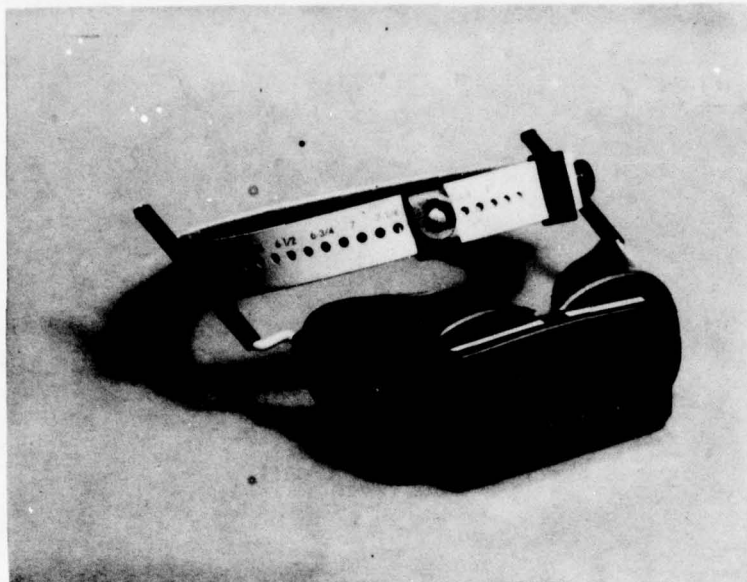


Figure 4. Headrest flexible goggles.



Figure 5. Coverall-type flexible vinyl goggles.

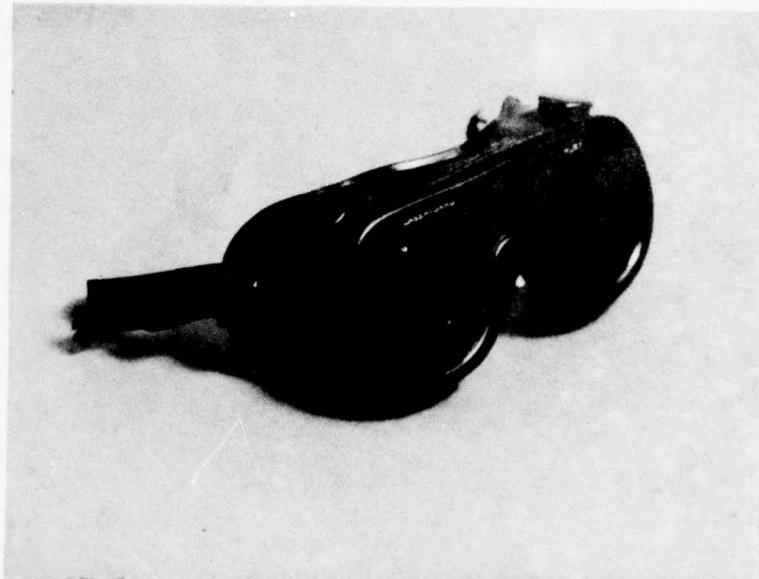


Figure 6. Full-view soft vinyl goggles.

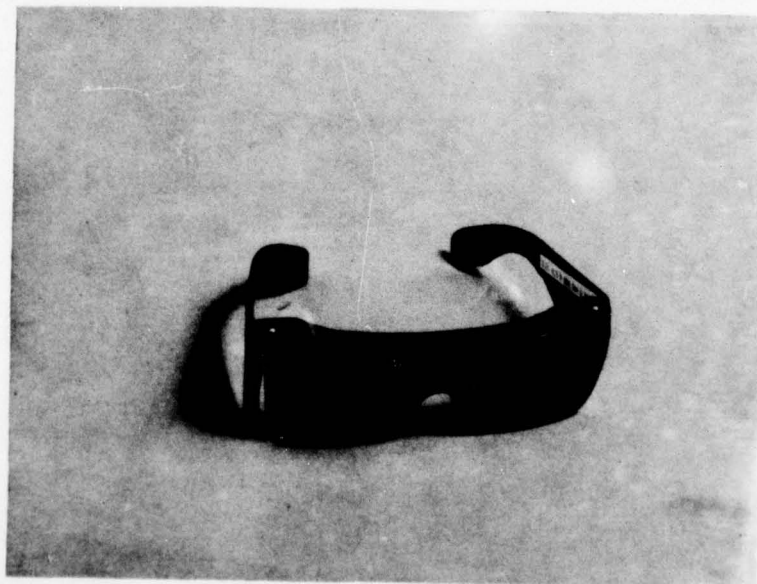


Figure 7. Full-view hard plastic spectacles with side shields.



Figure 8. Air Force aircrew helmet with laser-protection visor.

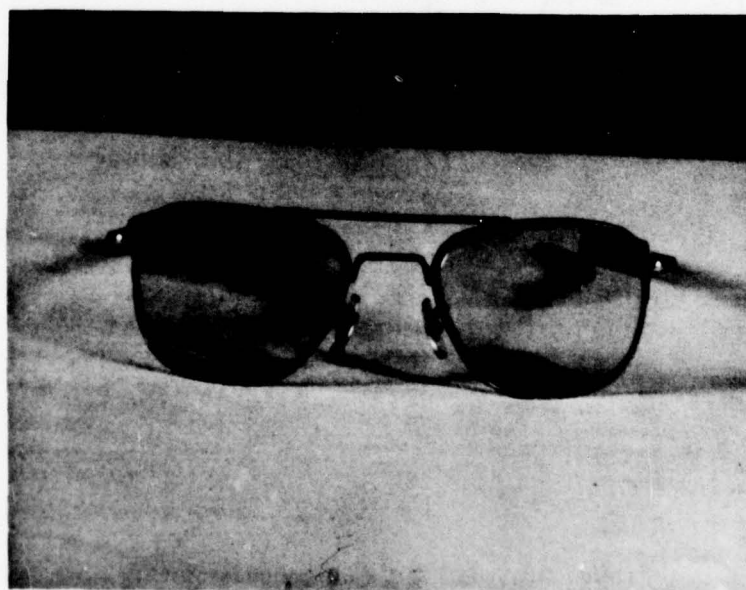


Figure 9. Air Force aircrew spectacles.

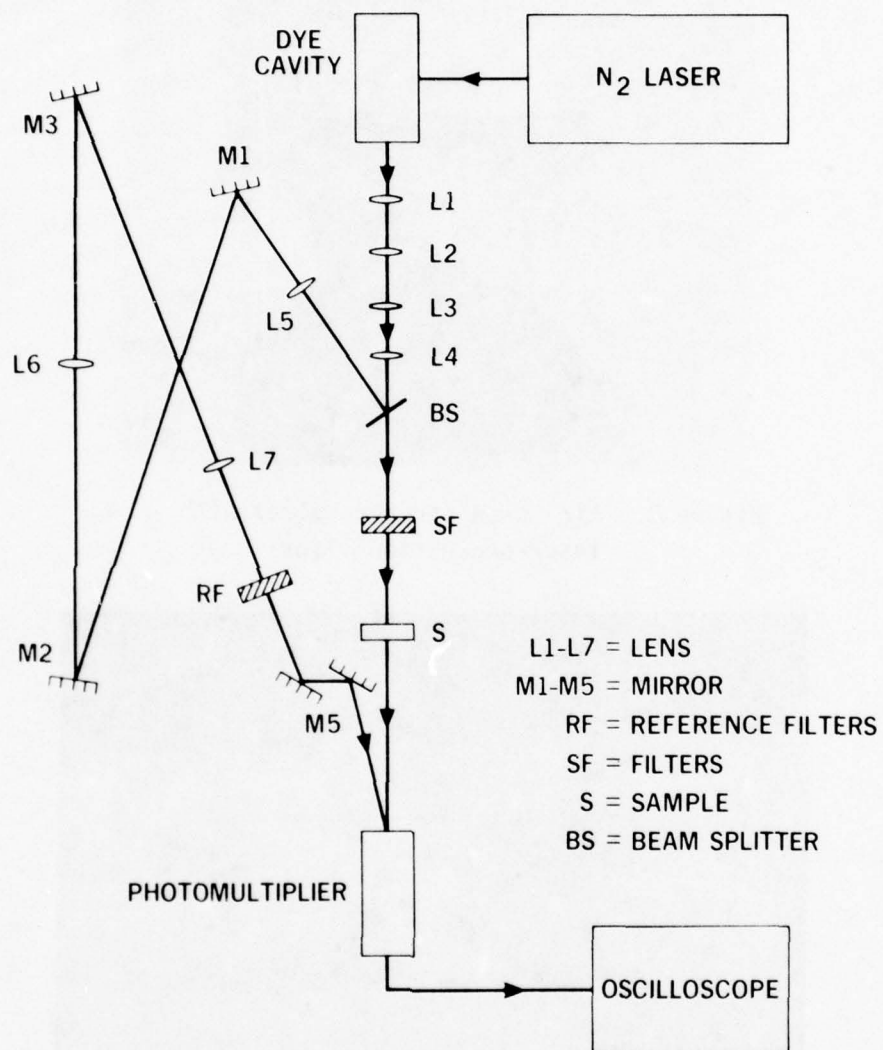


Figure 10. Pulsed laser densitometer.

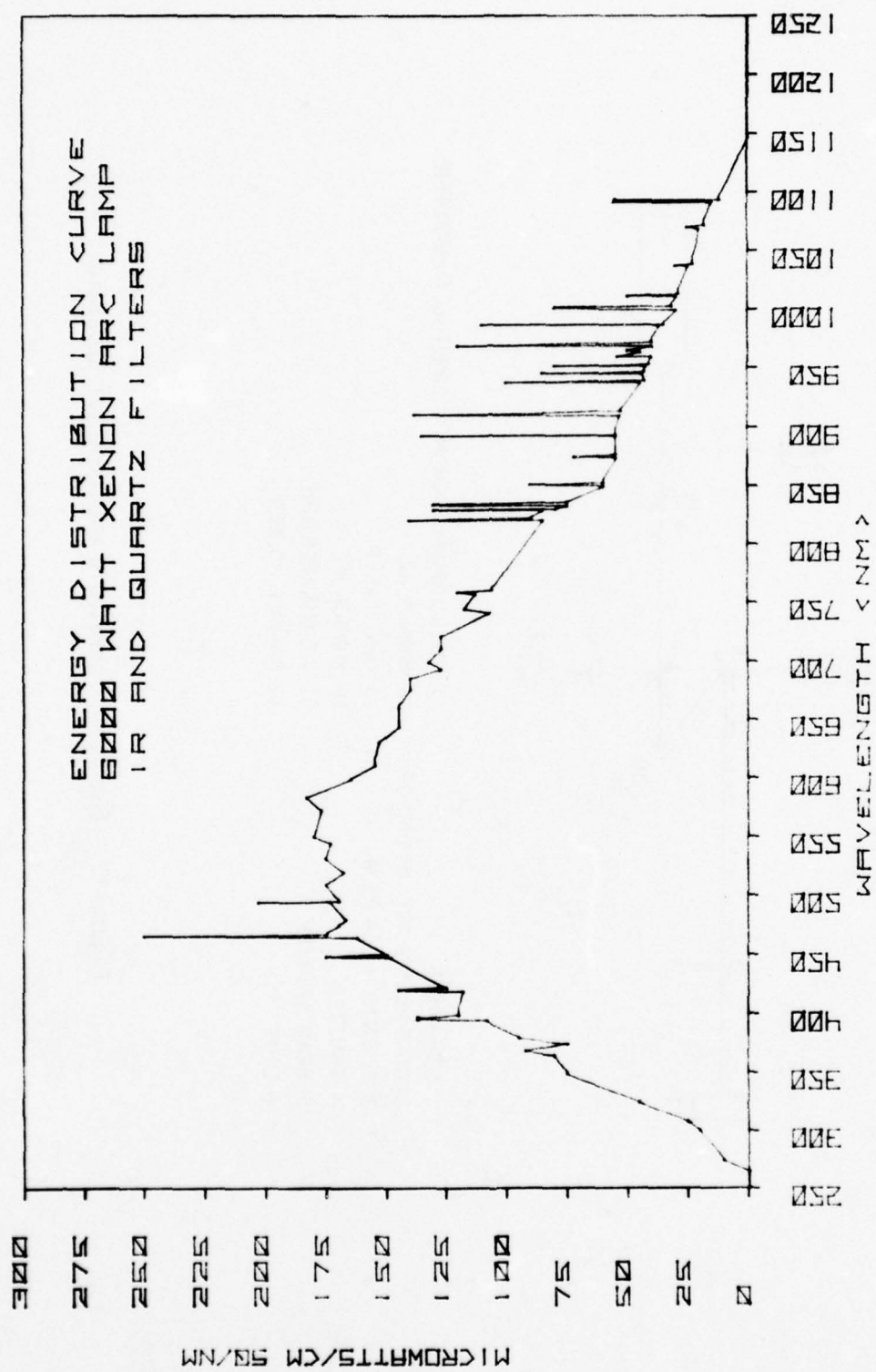
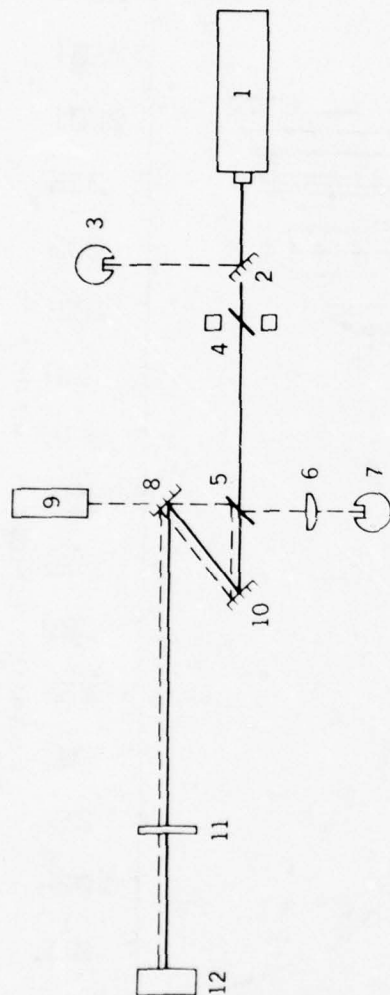


Figure 11. Environmental chamber's energy distribution curve.



- | | |
|-----------------------------|---|
| 1 CO ₂ LASER | 7. THERMOPILE (HADRON 101) (KEITHLEY AMMETER) |
| 2 GOLD PLATED POP UP MIRROR | 8. MIRROR #2 |
| 3. SCIENTECH 364 P.E.M. | 9. HeNe LASER |
| 4 SHUTTER | 10. MIRROR #3 |
| 5. BEAM SPLITTER | 11. 7.5 MM APERTURE |
| 6 LENS | 12. SAMPLE HOLDER |

Figure 12. CO₂ damage threshold experimental apparatus.

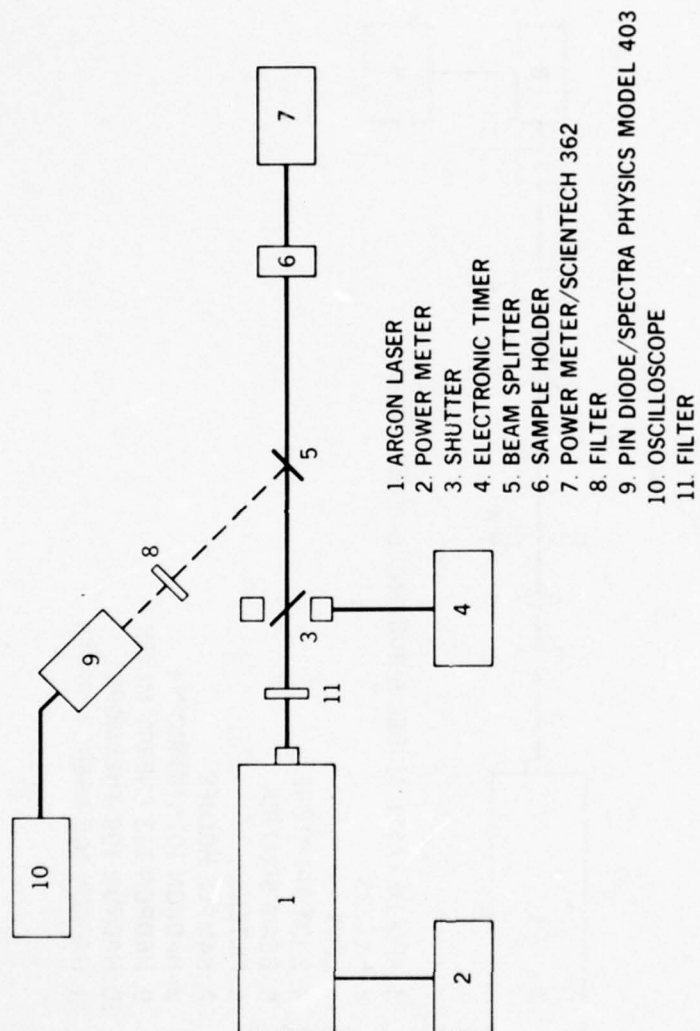


Figure 13. Argon damage threshold experimental apparatus.

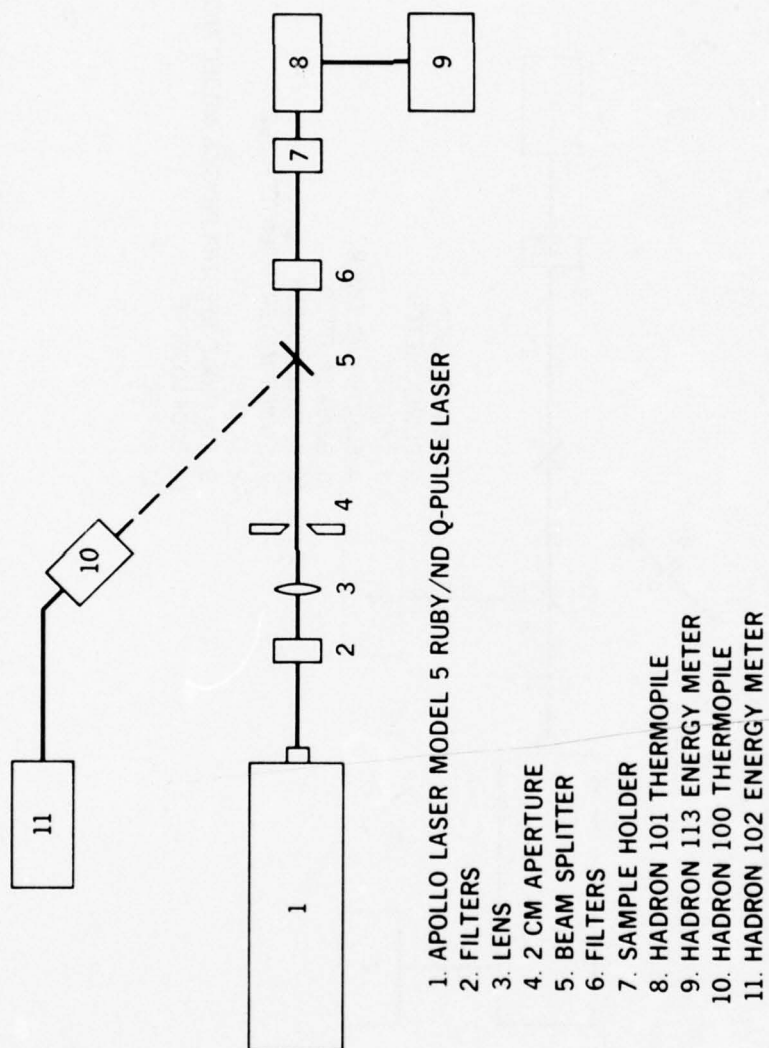


Figure 14. Ruby damage threshold irreversible bleaching experimental apparatus.

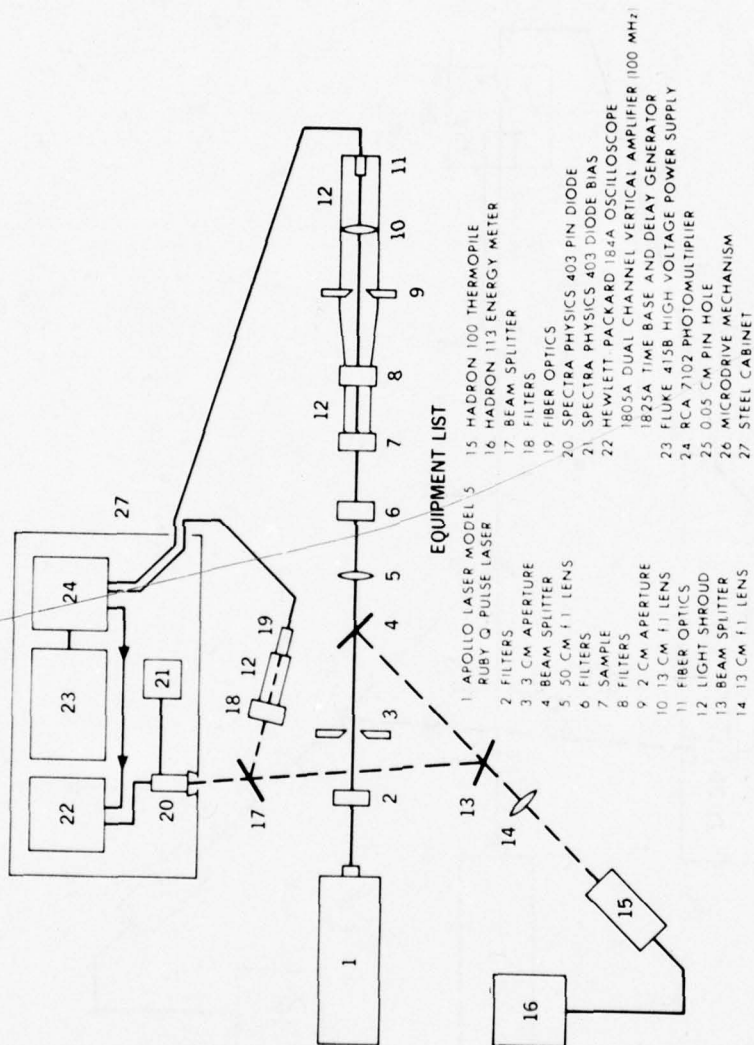
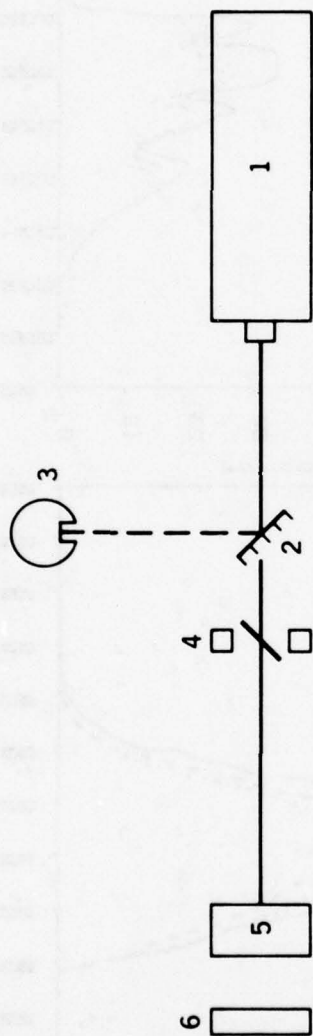


Figure 15. Arrangement of apparatus for measurement of reversible bleaching.





1. CO₂ LASER
2. GOLD-PLATED POP-UP MIRROR (MIRROR #1)
3. SCIENTECH 364 POWER ENERGY METER
4. SHUTTER
5. SAMPLE HOLDER
6. GAS VACUUM COLLECTION PROBE (ABOVE SAMPLE)

Figure 17. CO₂ fume analysis experimental apparatus.

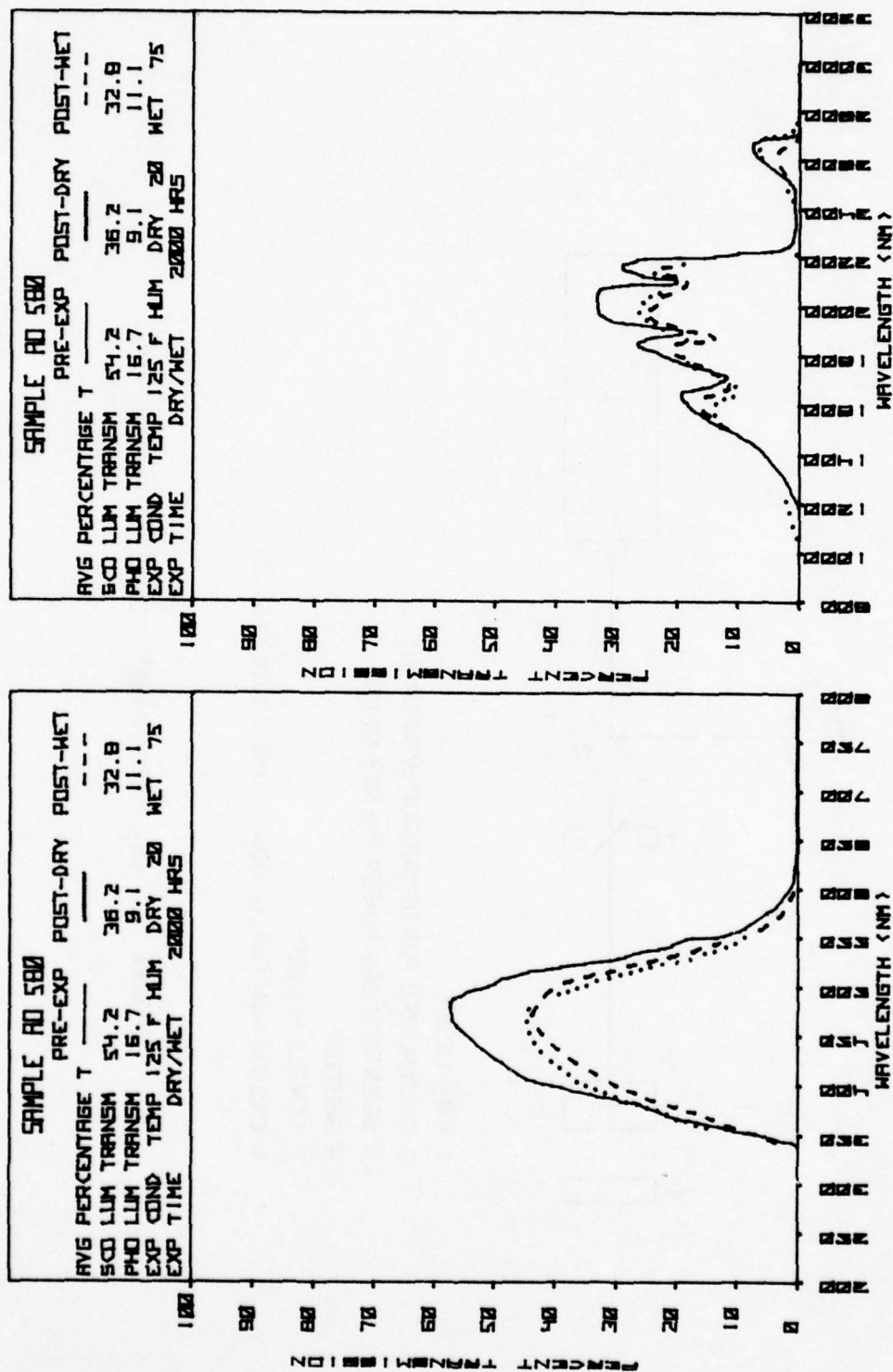


Figure 18. Environmental effects--AO 580-UV-visible range.

Figure 19. Environmental effects--AO 580-NIR range.

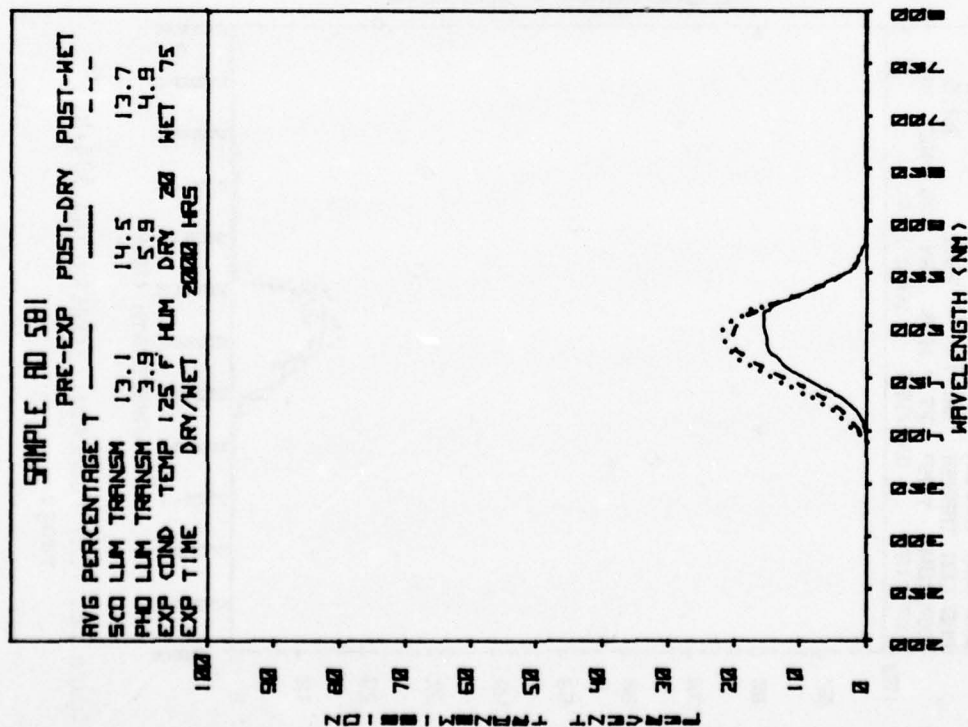


Figure 20. Environmental effects--AO 581-UV-visible range.

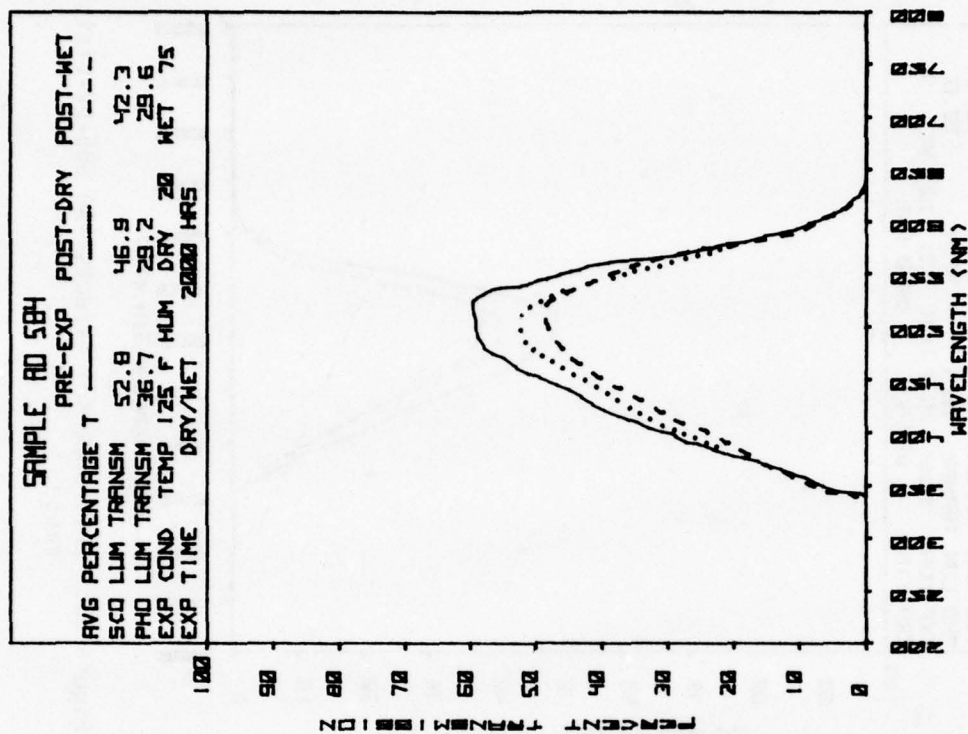


Figure 21. Environmental effects--AO 584-UV-visible range.

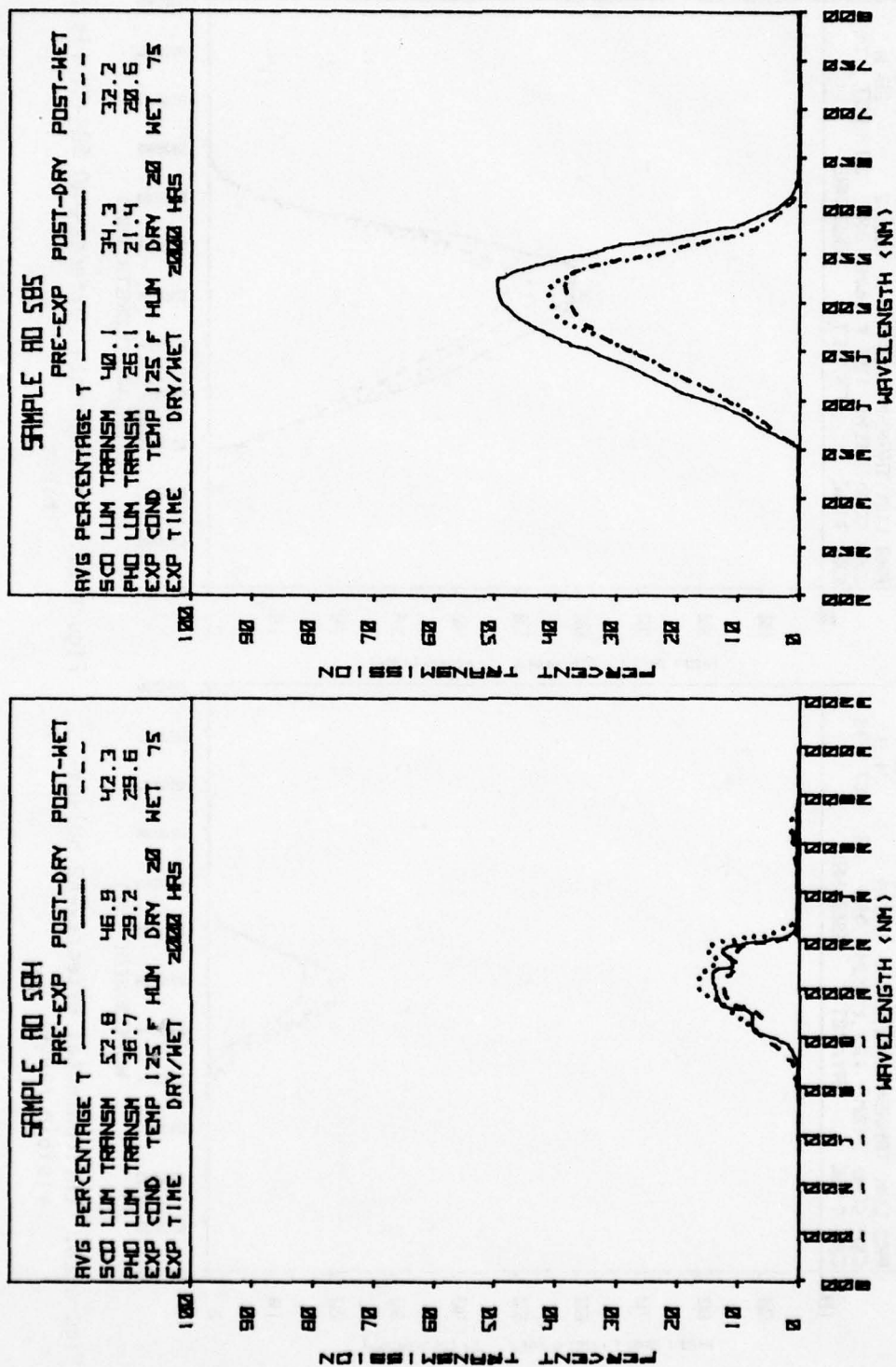


Figure 22. Environmental effects--AO 584-NIR range.

Figure 23. Environmental effects--AO 585-UV-visible range.

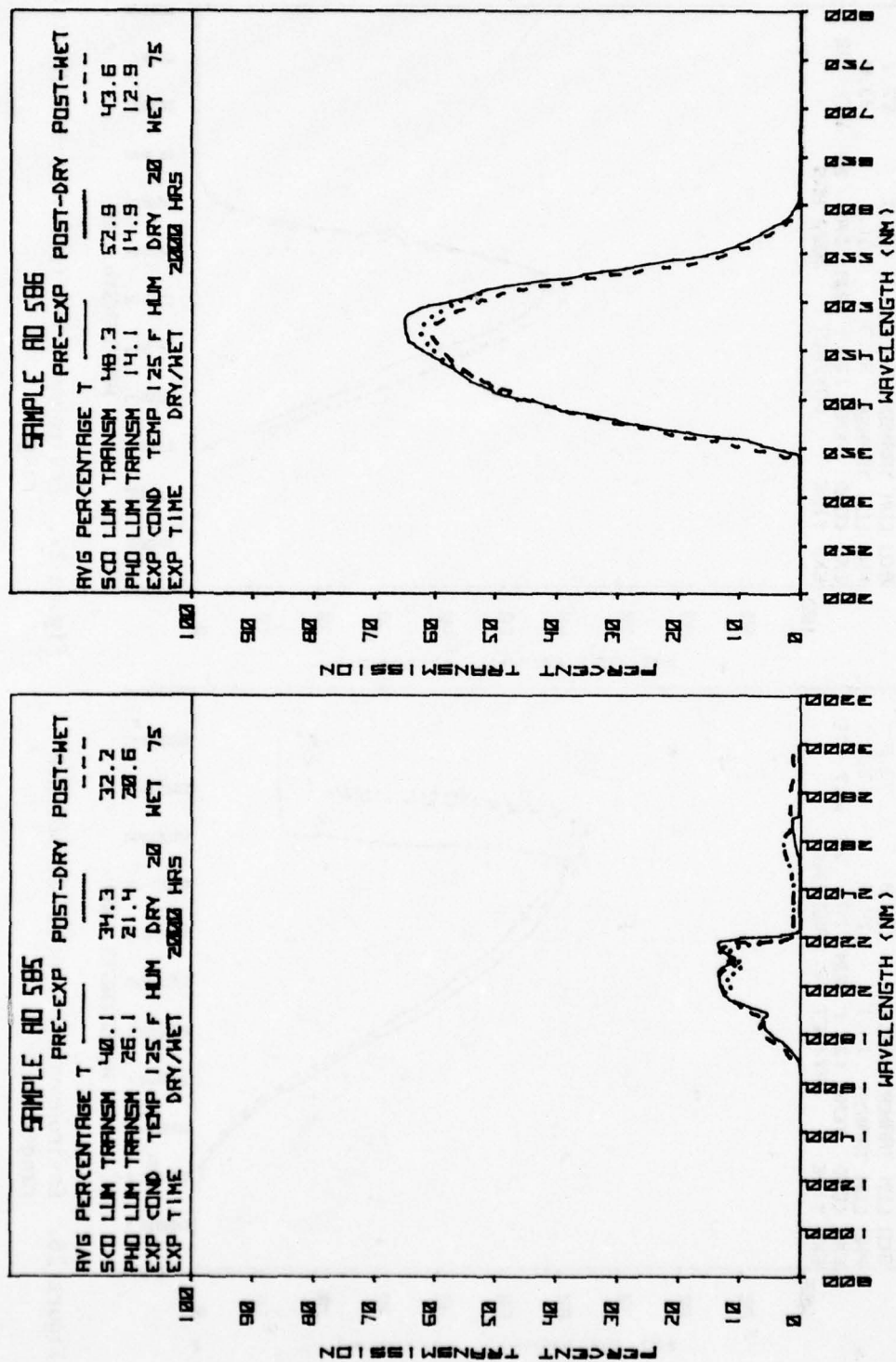


Figure 24. Environmental effects--A0 585-NIR range.

Figure 25. Environmental effects--A0 586-UV-visible range.

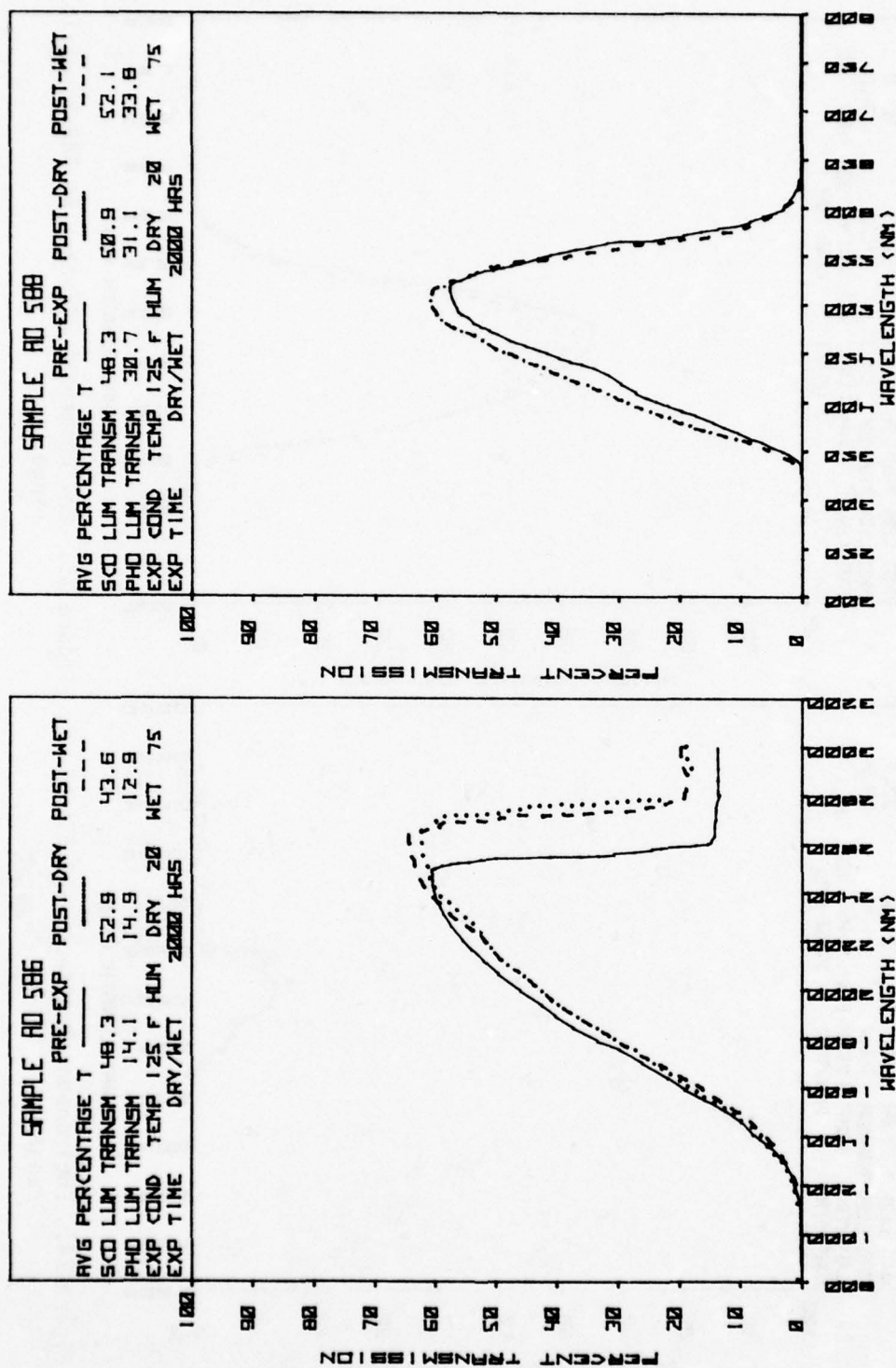


Figure 26. Environmental effects--A0 586-NIR range.

Figure 27. Environmental effects--A0 588-UV-visible range.

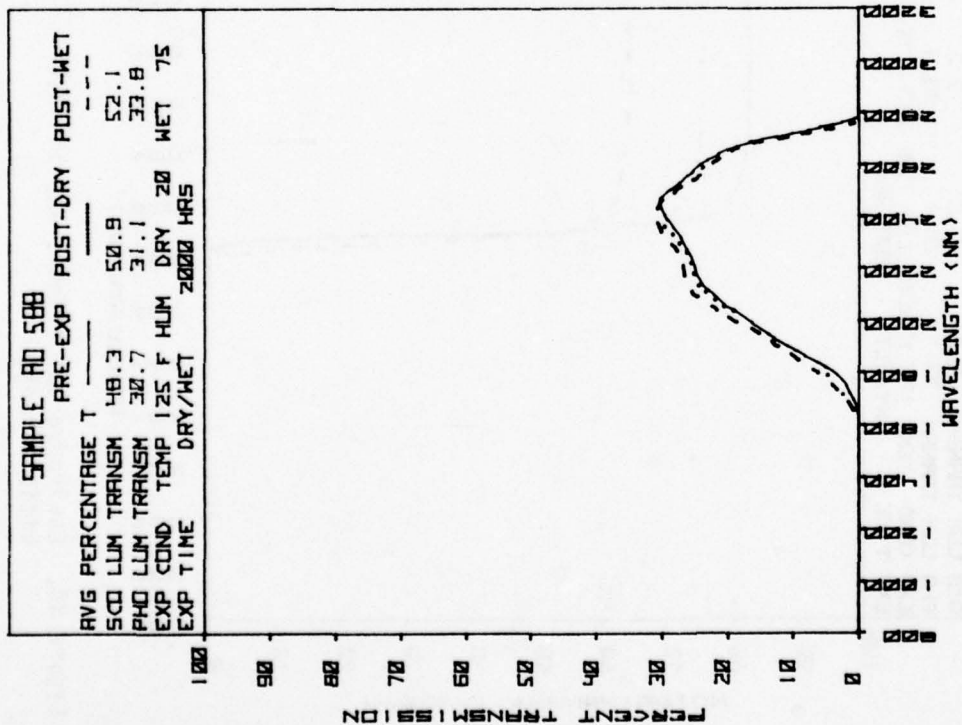


Figure 28. Environmental effects--A0 588-NIR range.

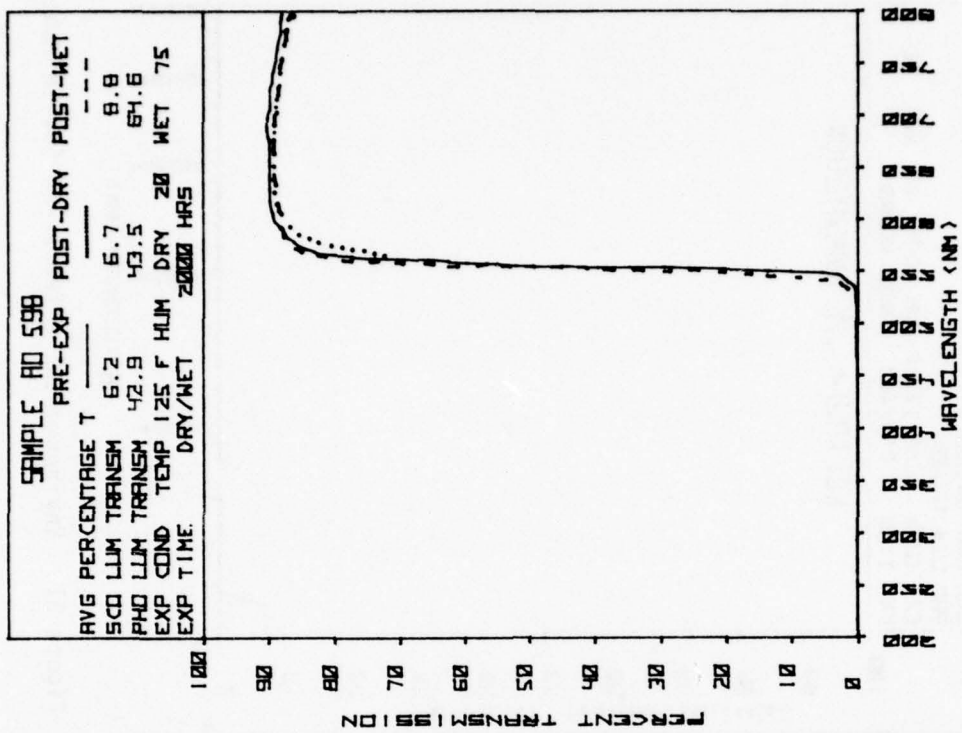


Figure 29. Environmental effects--A0 598-UV-visible range.

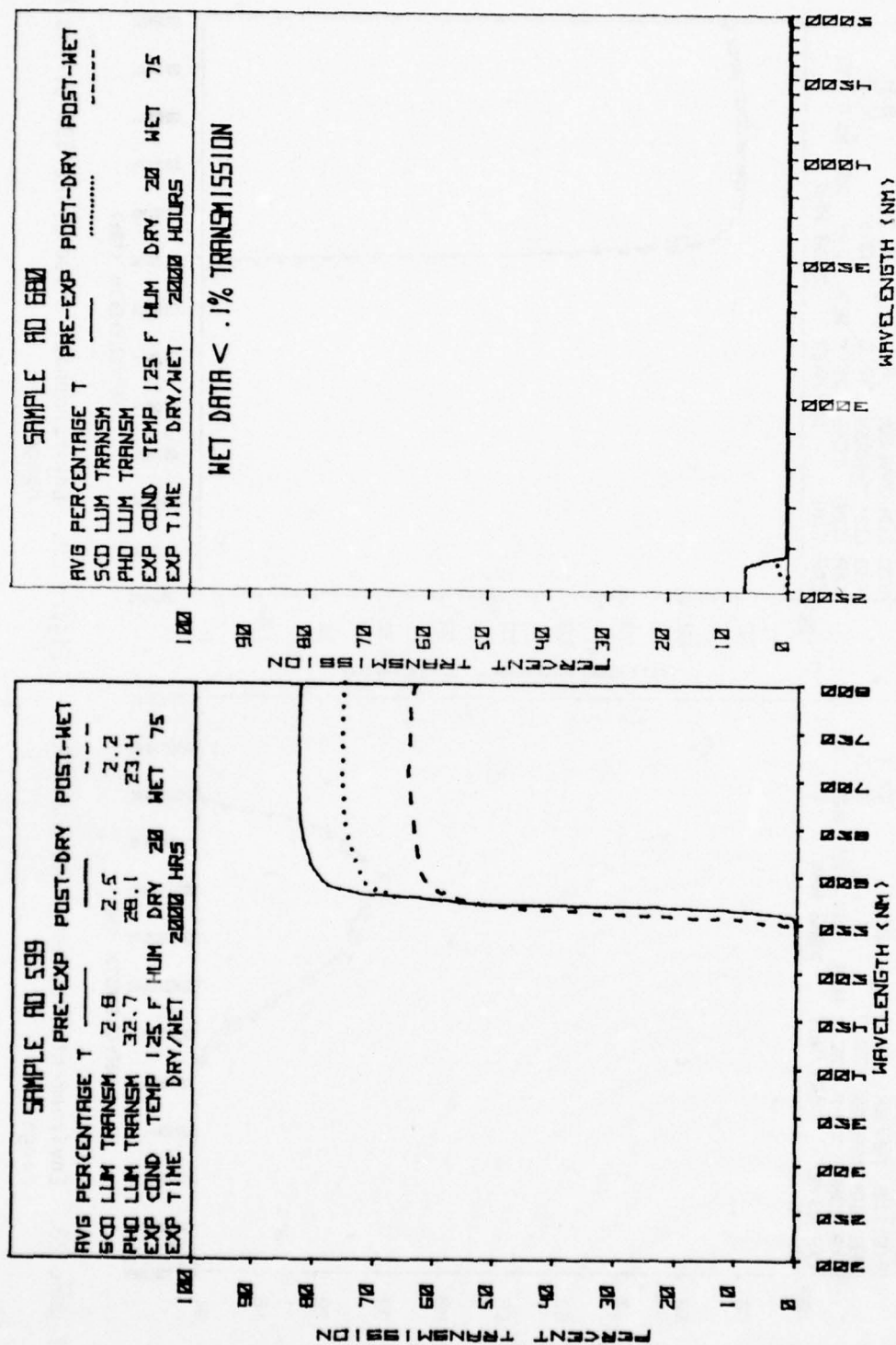


Figure 30. Environmental effects--AO 599-UV-
visible range.

Figure 31. Environmental effects--AO 680-IR range.

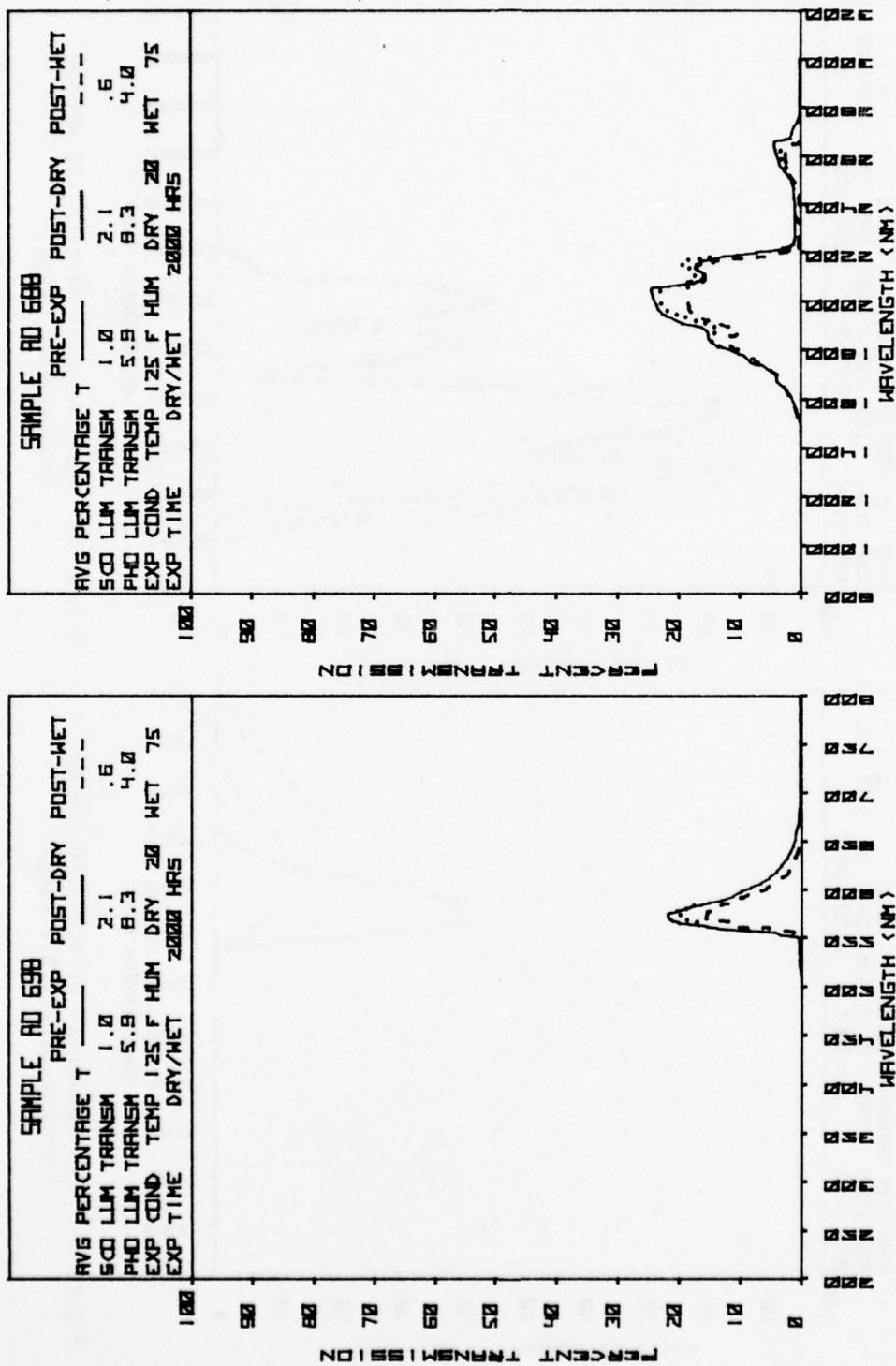


Figure 32. Environmental effects--A0 698-UV-visible range.

Figure 33. Environmental effects--A0 688-NIR range.

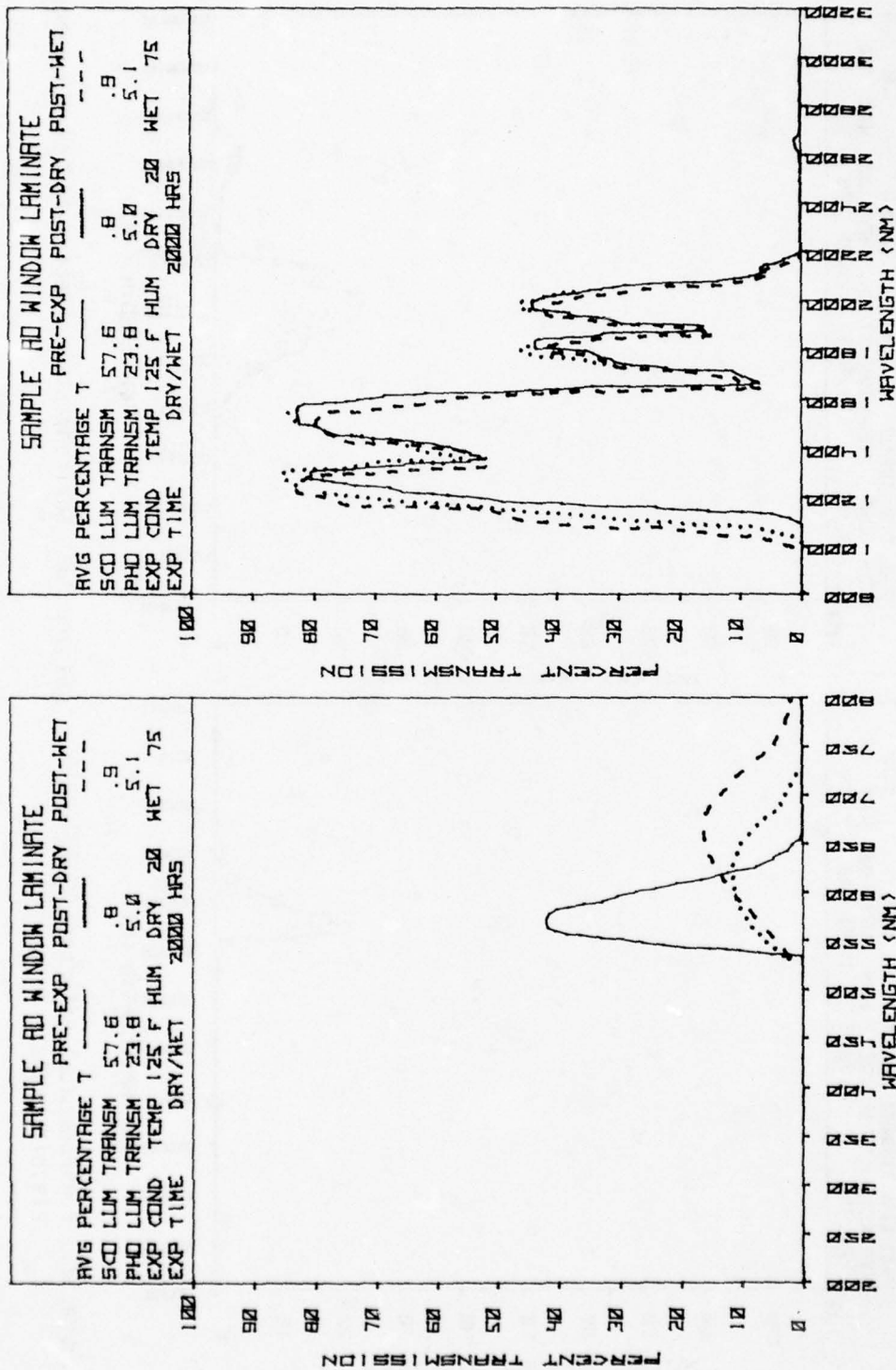


Figure 34. Environmental effects--A0 window laminate-UV-visible range.

Figure 35. Environmental effects--A0 window laminate-NIR range.

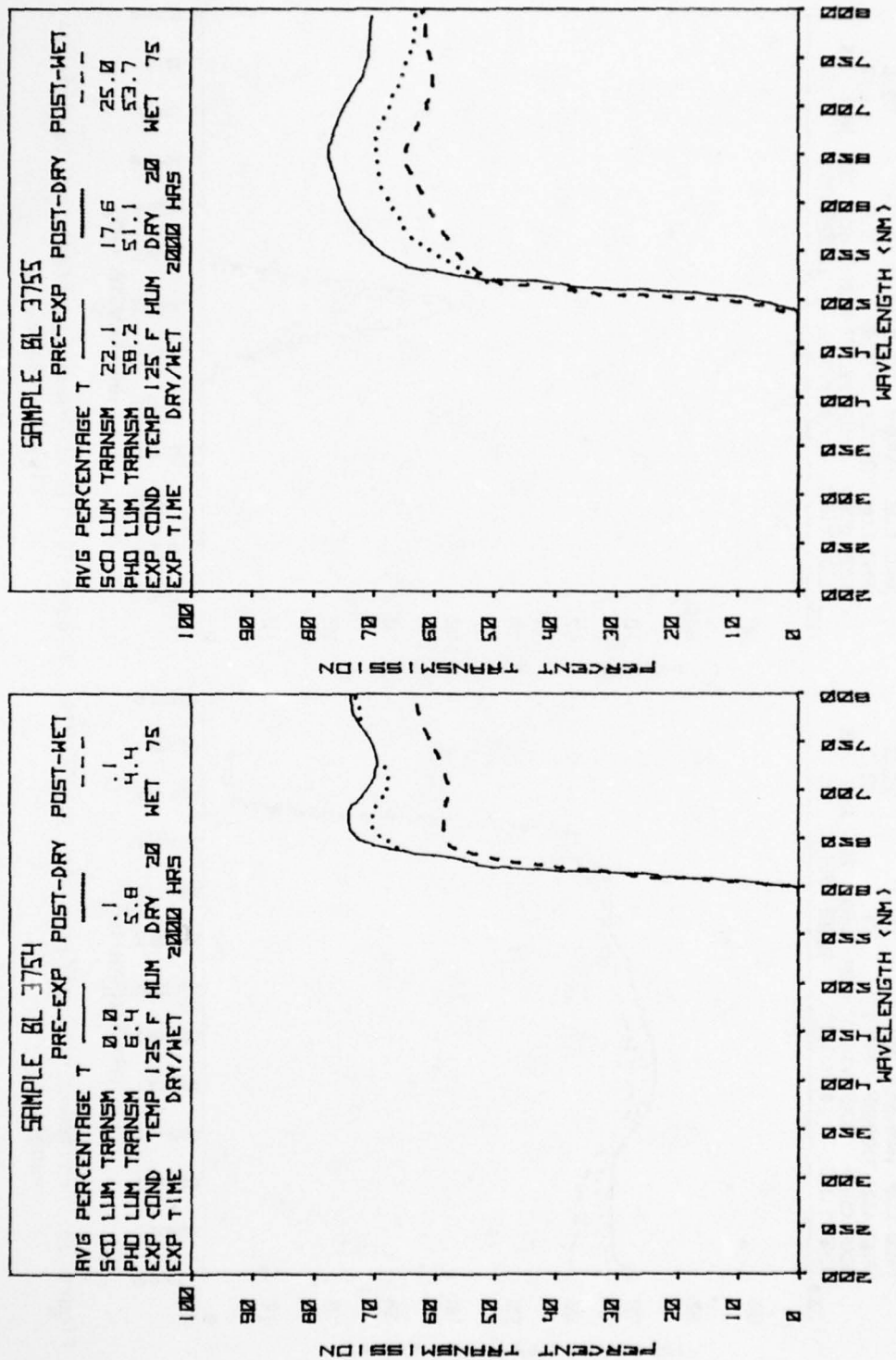


Figure 36. Environmental effects--BL 5W3754-UV-visible range.

Figure 37. Environmental effects--BL 5W3755-UV-visible range.

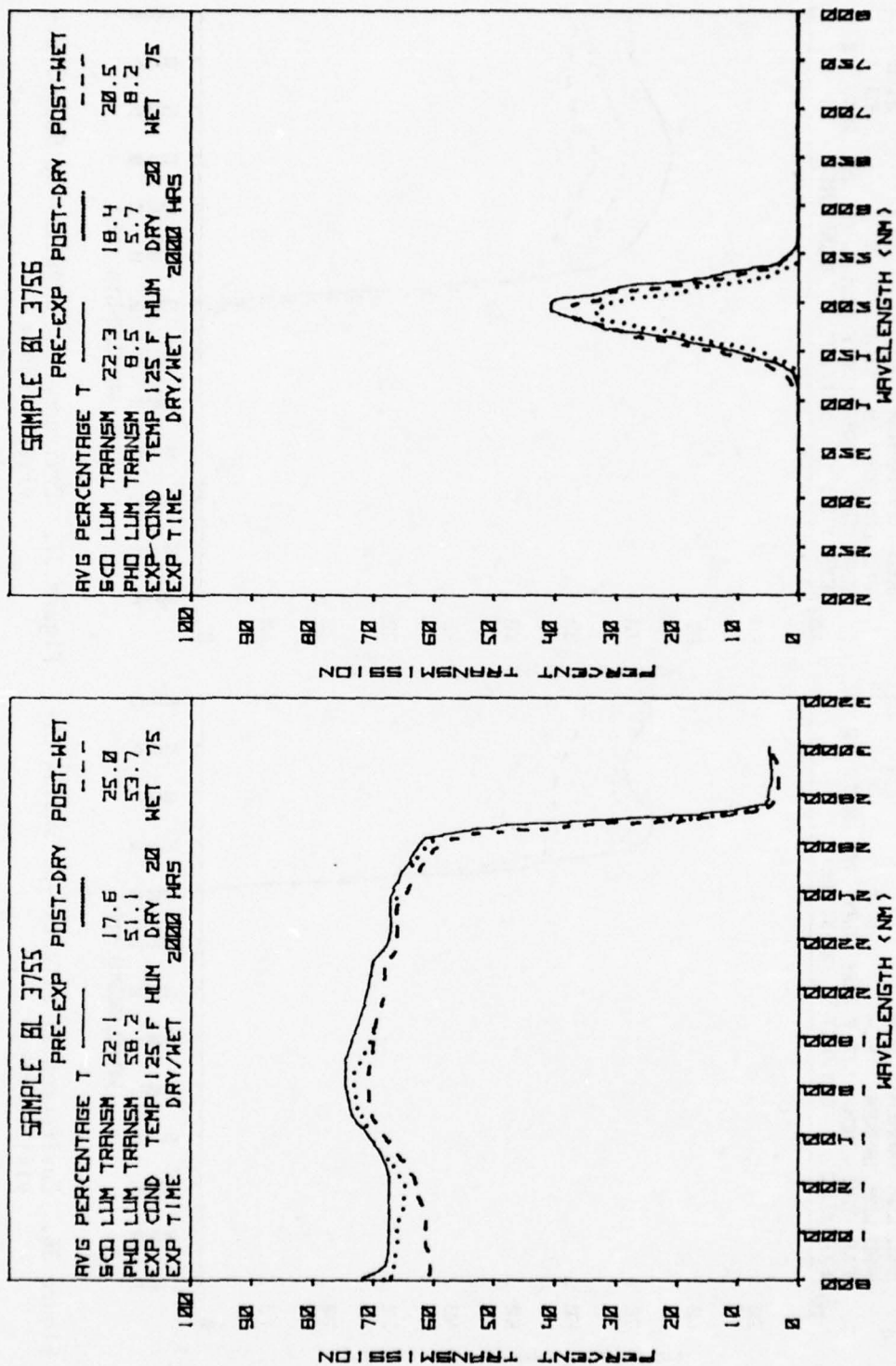


Figure 39. Environmental effects--BL 3756-UV-visible range.

Figure 38. Environmental effects--BL 3755-NIR range.

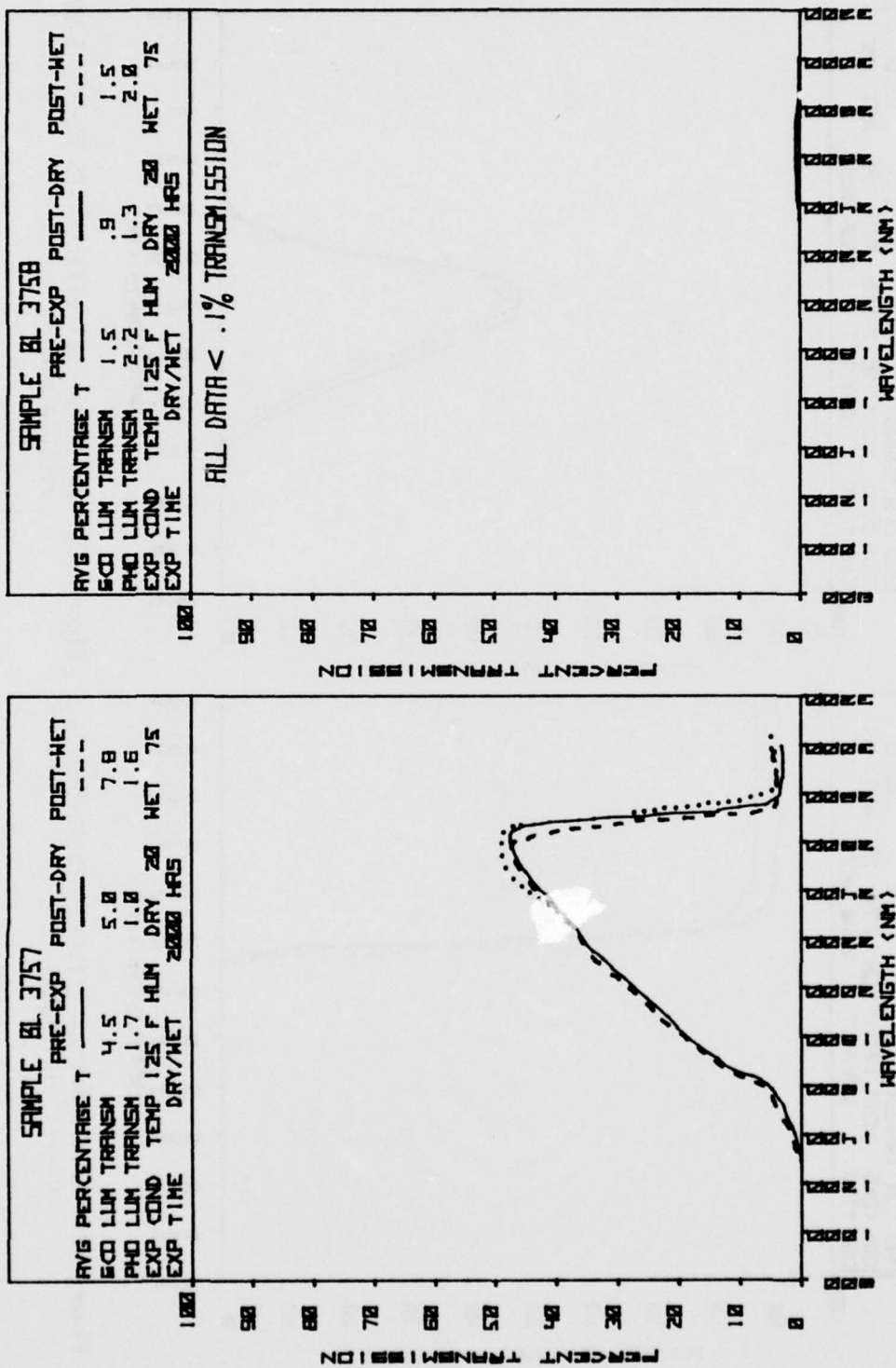


Figure 41. Environmental effects--BL 5W3758-NIR range.

Figure 40. Environmental effects--BL 5W3757-NIR range.

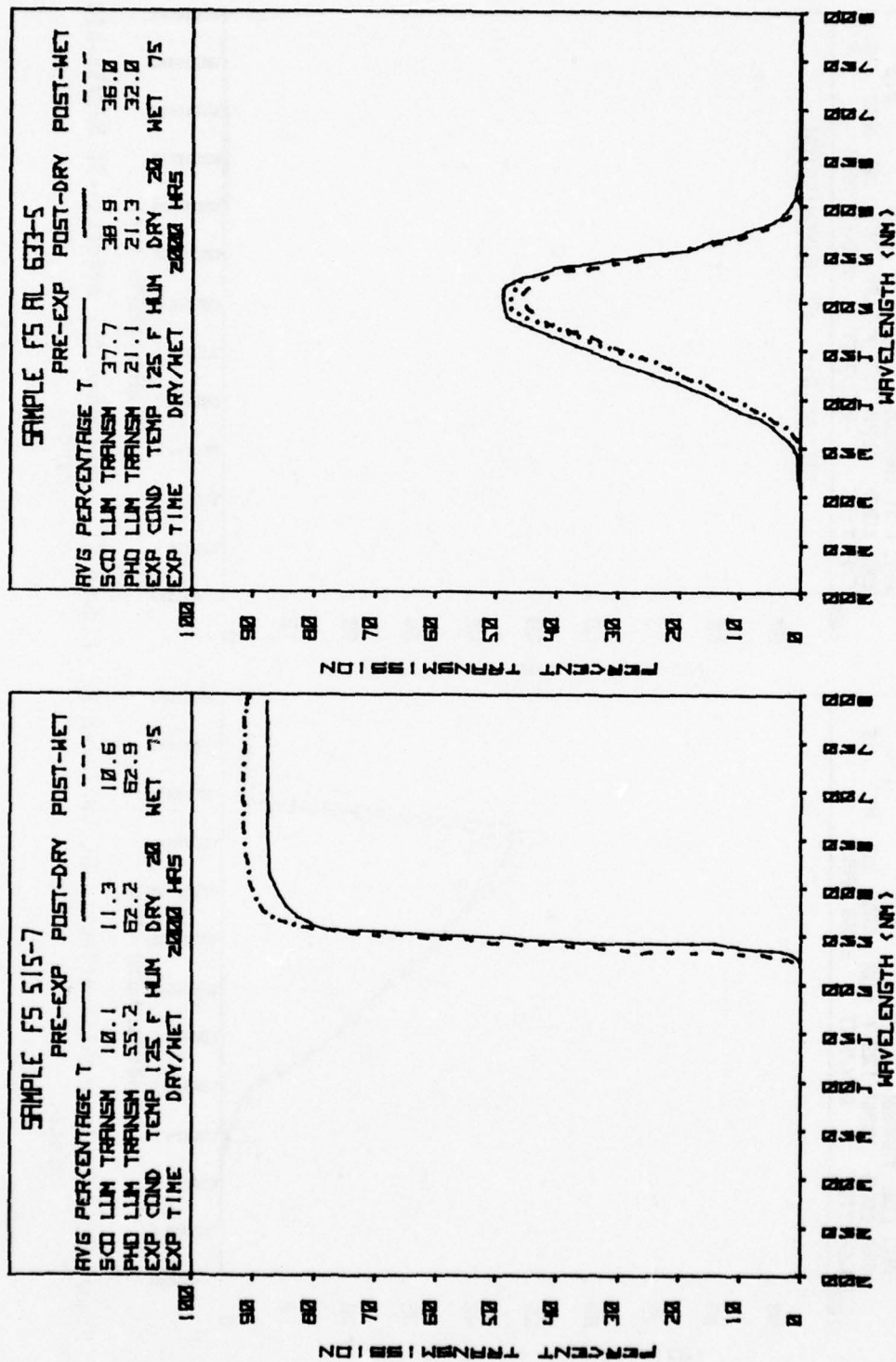


Figure 42. Environmental effects--FS AL-515-7-UV-visible range.

Figure 43. Environmental effects--FS AL-633-5-UV-visible range.

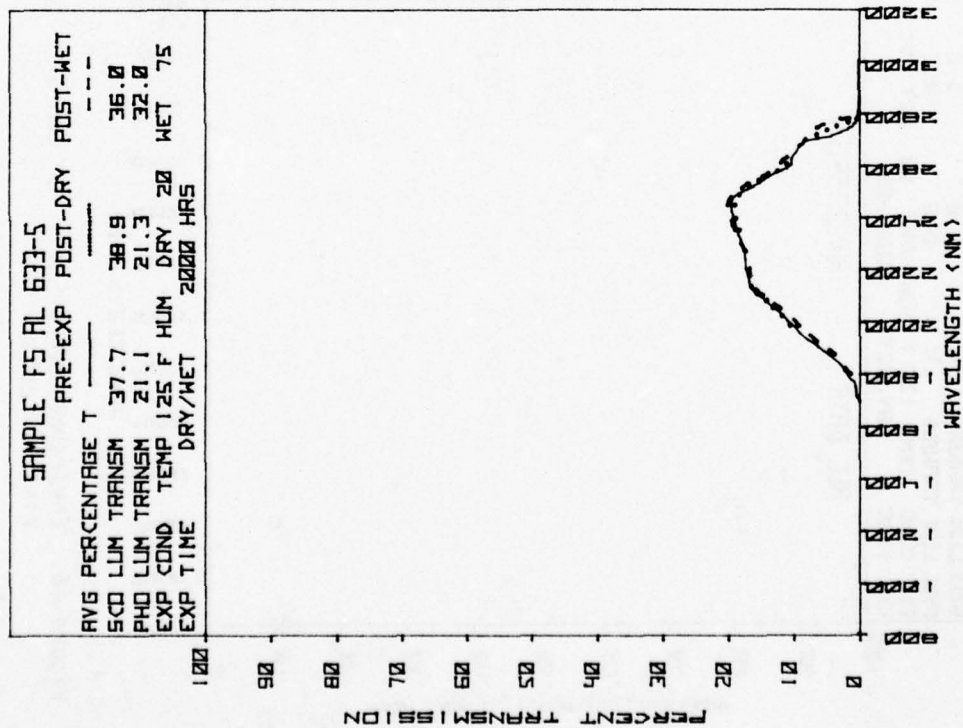


Figure 44. Environmental effects--FS AL-633-5-NIR range.

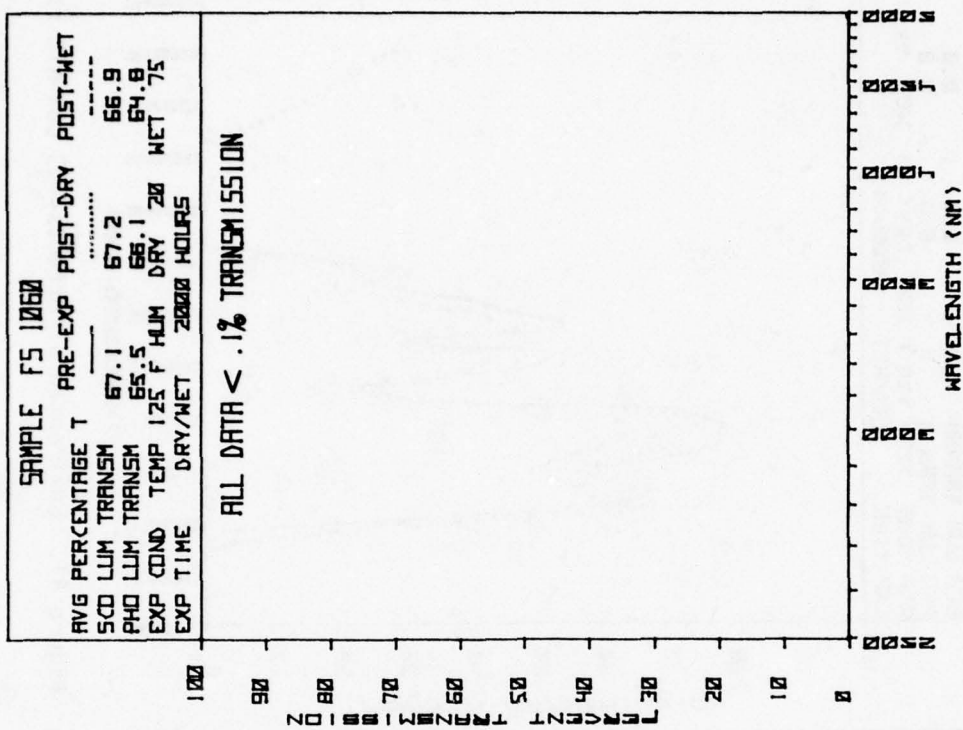


Figure 45. Environmental effects--FS AL-1060-IR range.

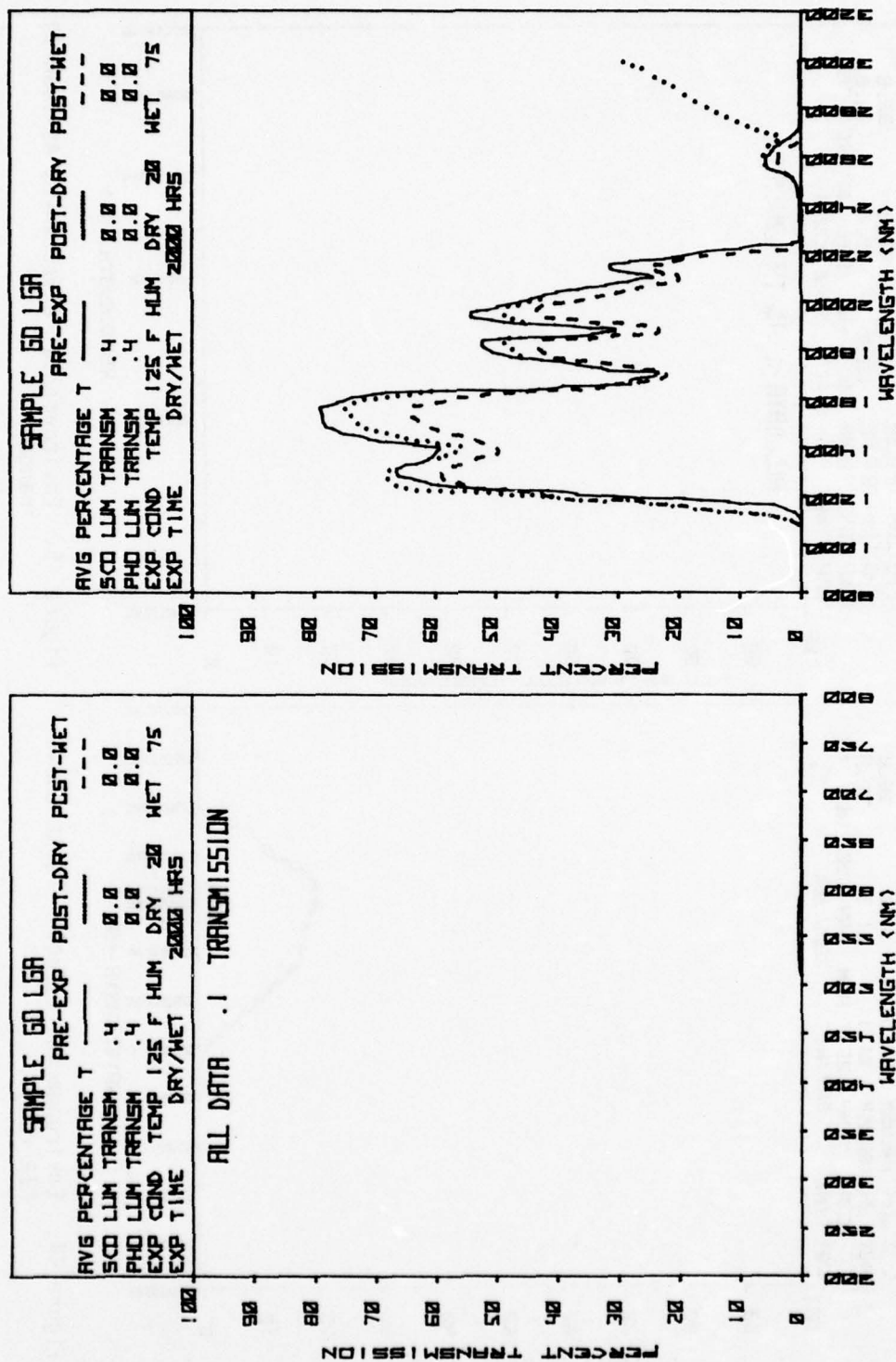


Figure 46. Environmental effects--GO LGA-UV-visible range.

Figure 47. Environmental effects--GO LGA-NIR range.

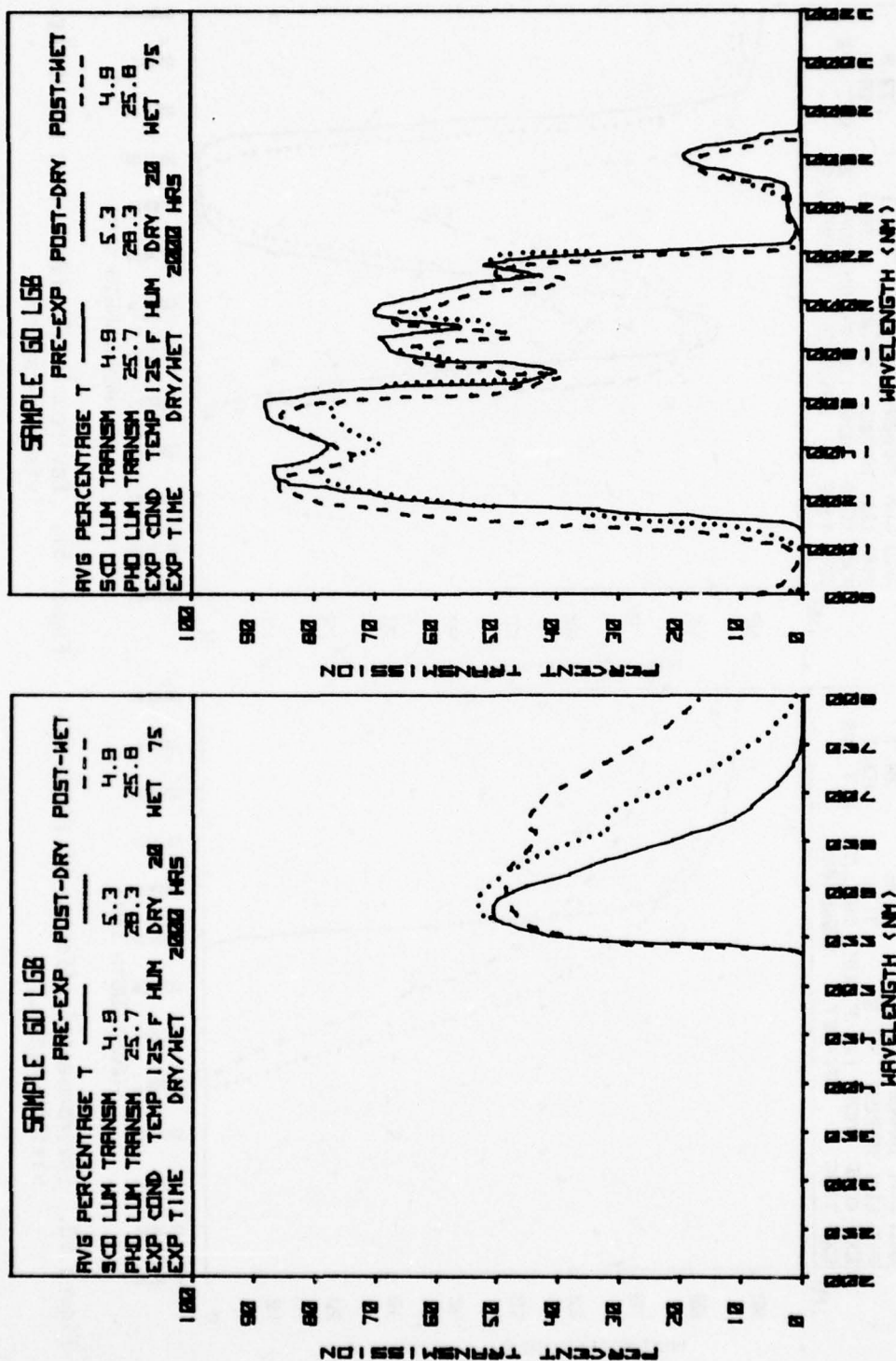
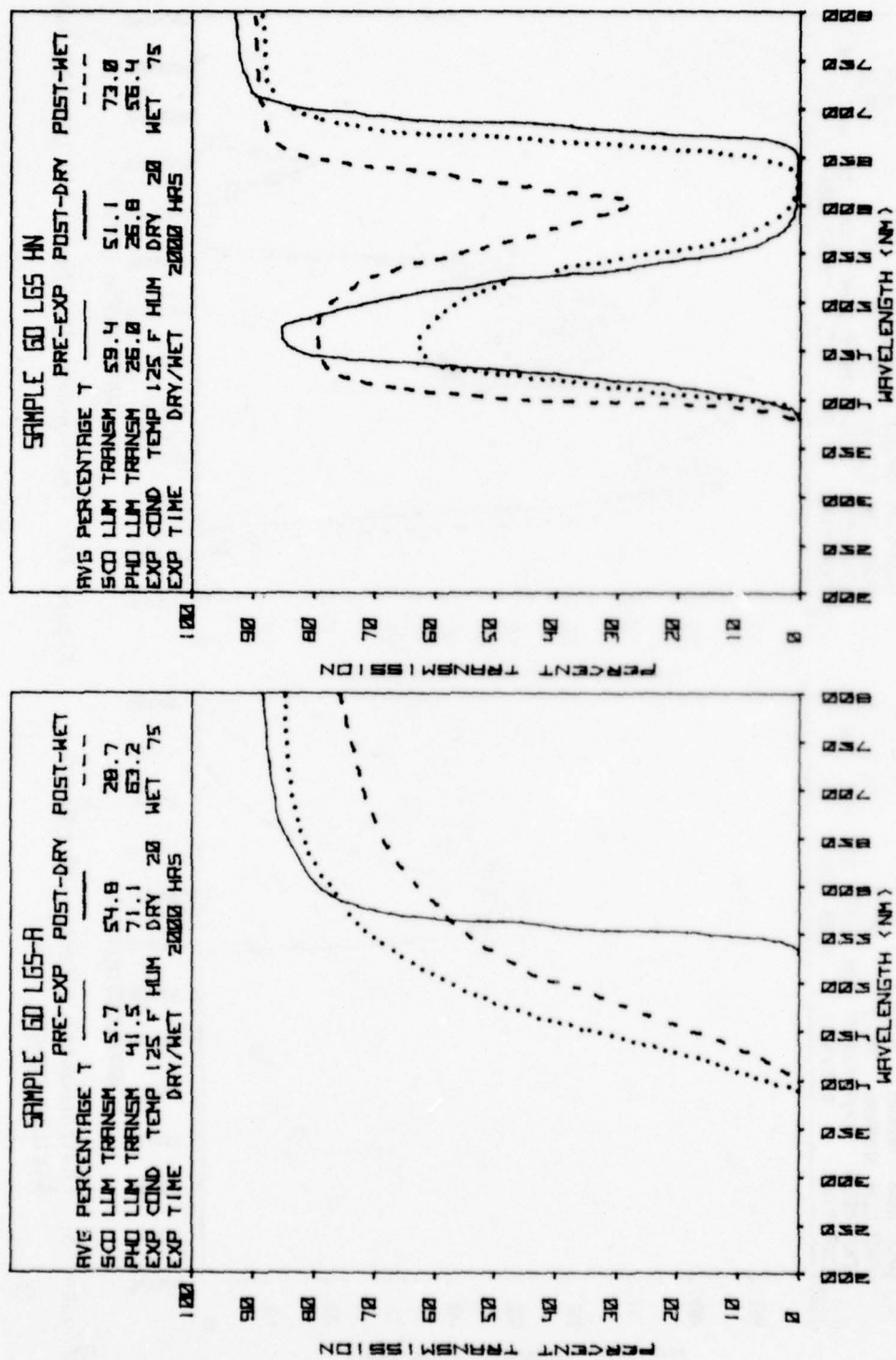
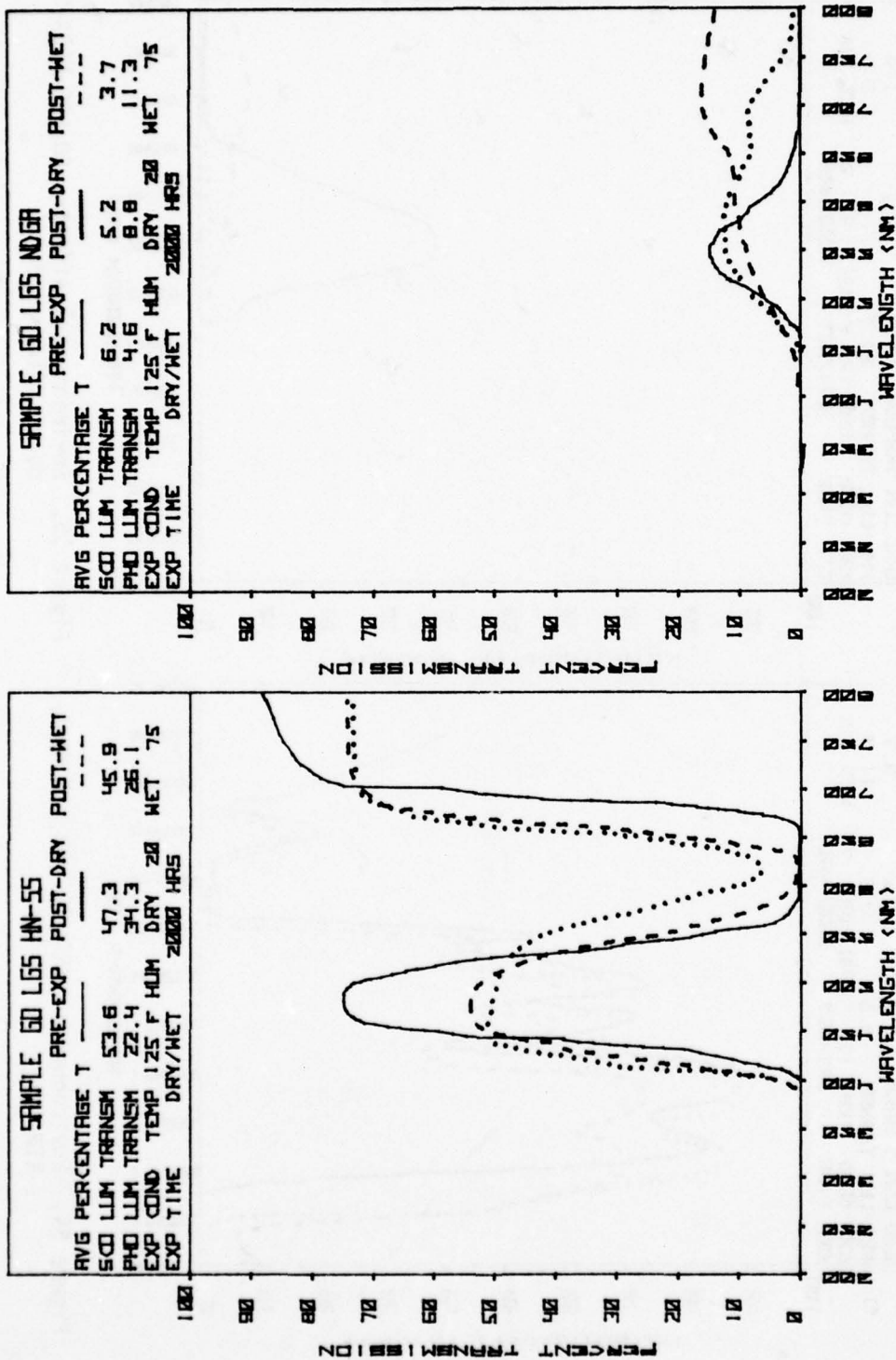


Figure 48. Environmental effects--GO LGB-UV-visible range.

Figure 49. Environmental effects--GO LGB-NIR range.





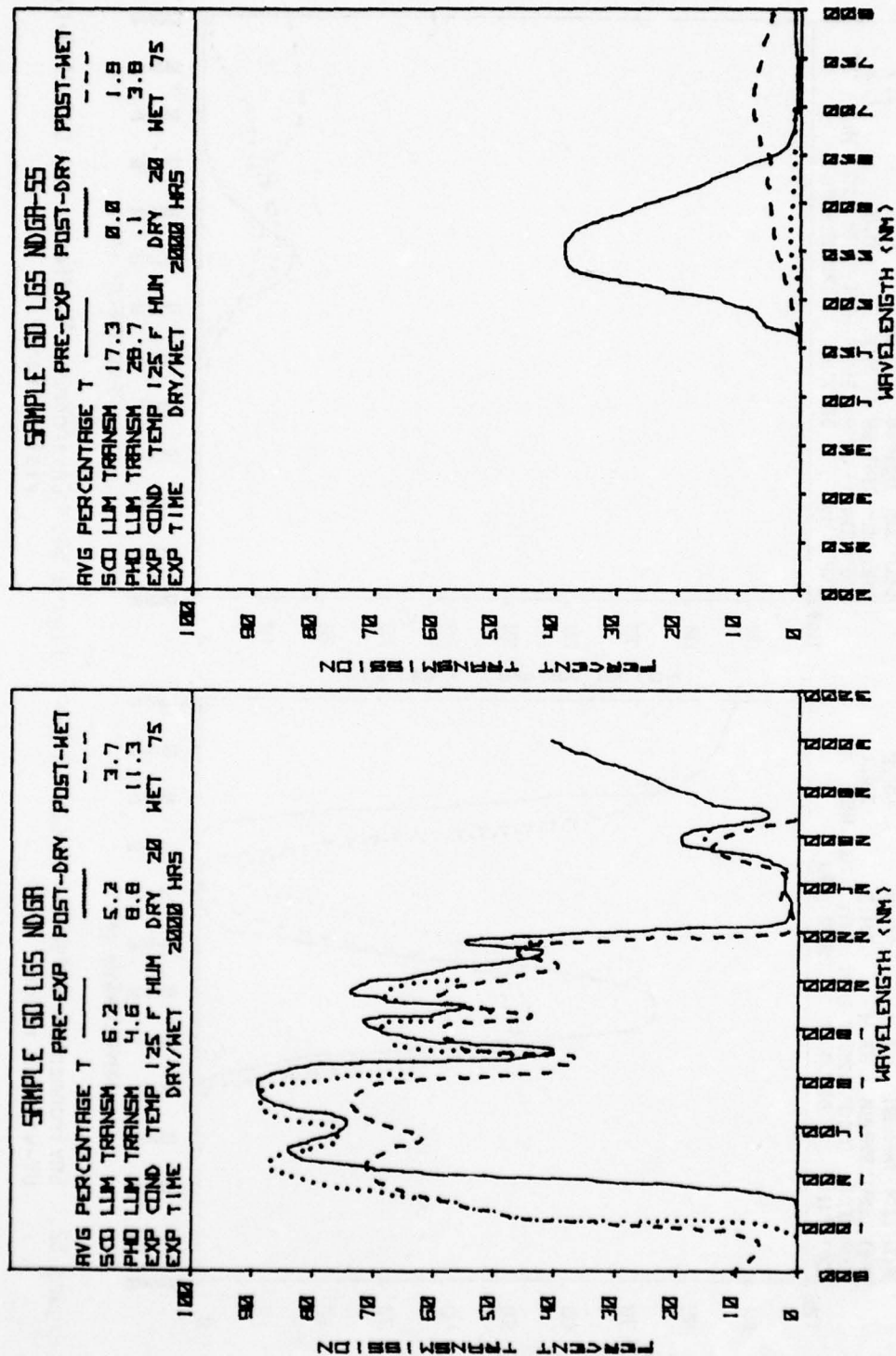


Figure 54. Environmental effects--GO LGS-NDGA--NIR range.

Figure 55. Environmental effects--GO LGS-NDGA-SS--UV-visible range.

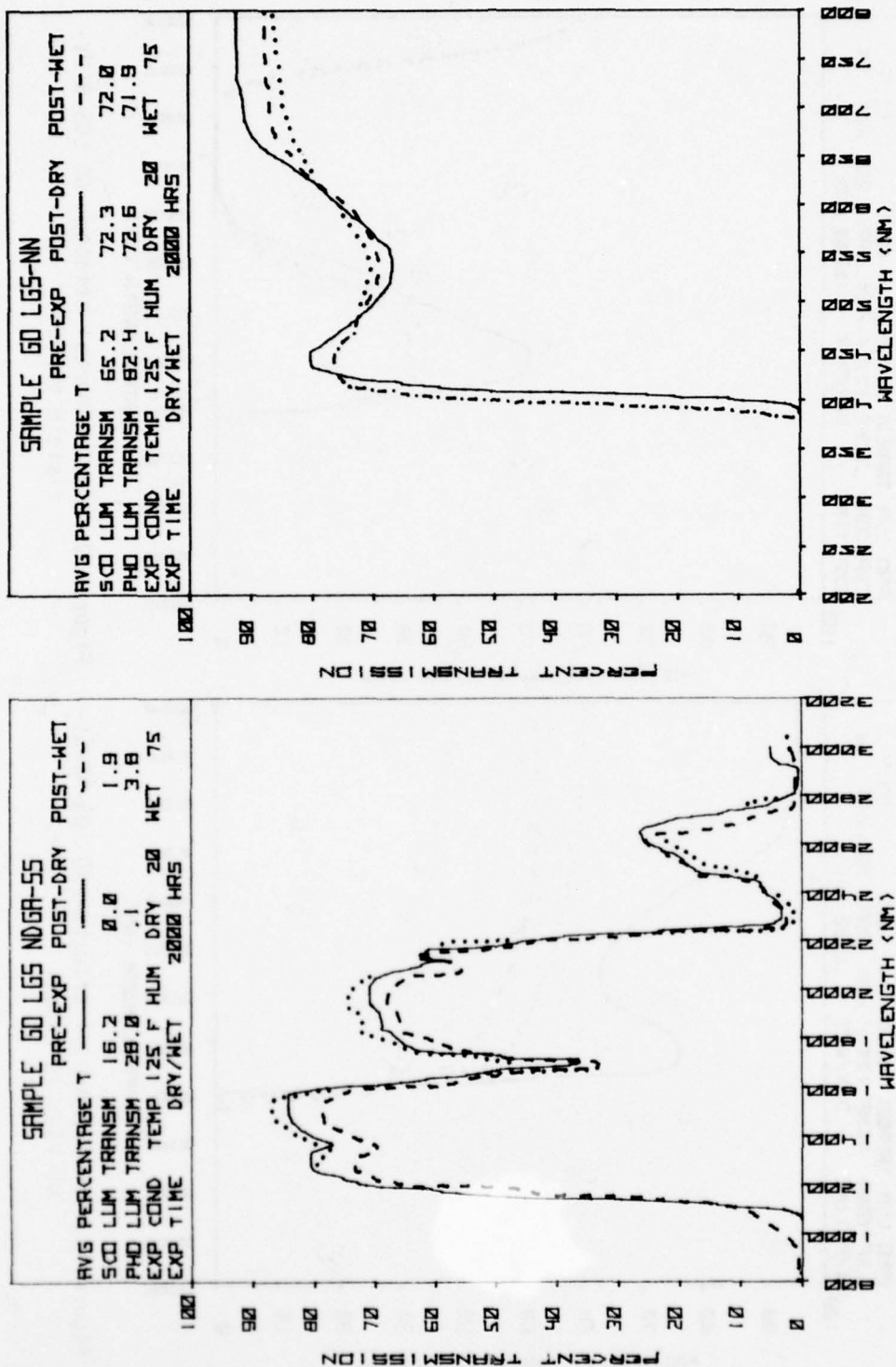


Figure 56. Environmental effects--G0 LGS-NDGA-SS-NIR range.

Figure 57. Environmental effects--G0 LGS-NN-UV-visible range.

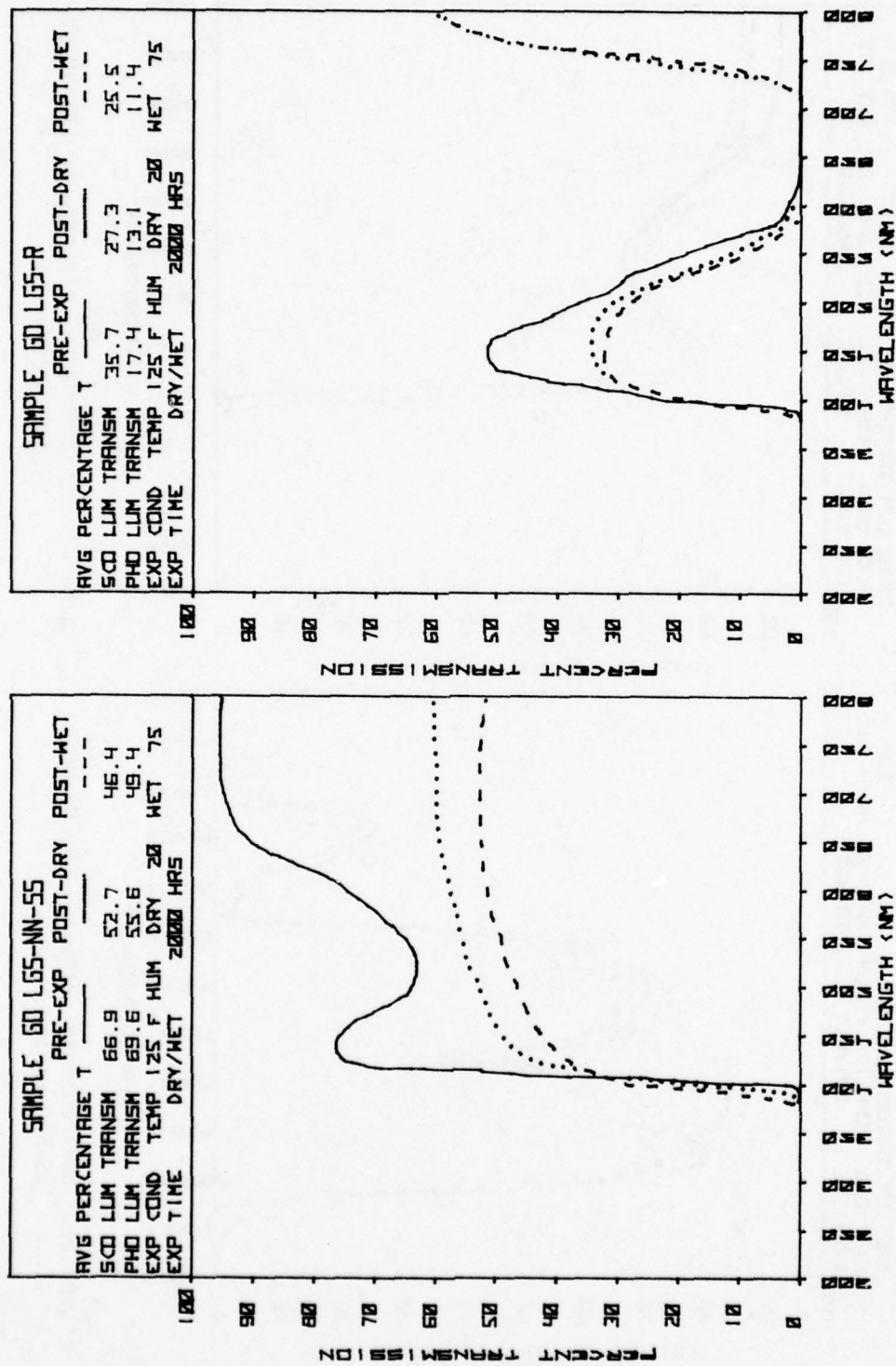


Figure 58. Environmental effects--60 LGS-NN-SS-UV-visible range.

Figure 59. Environmental effects--60 LGS-R-UV-visible range.

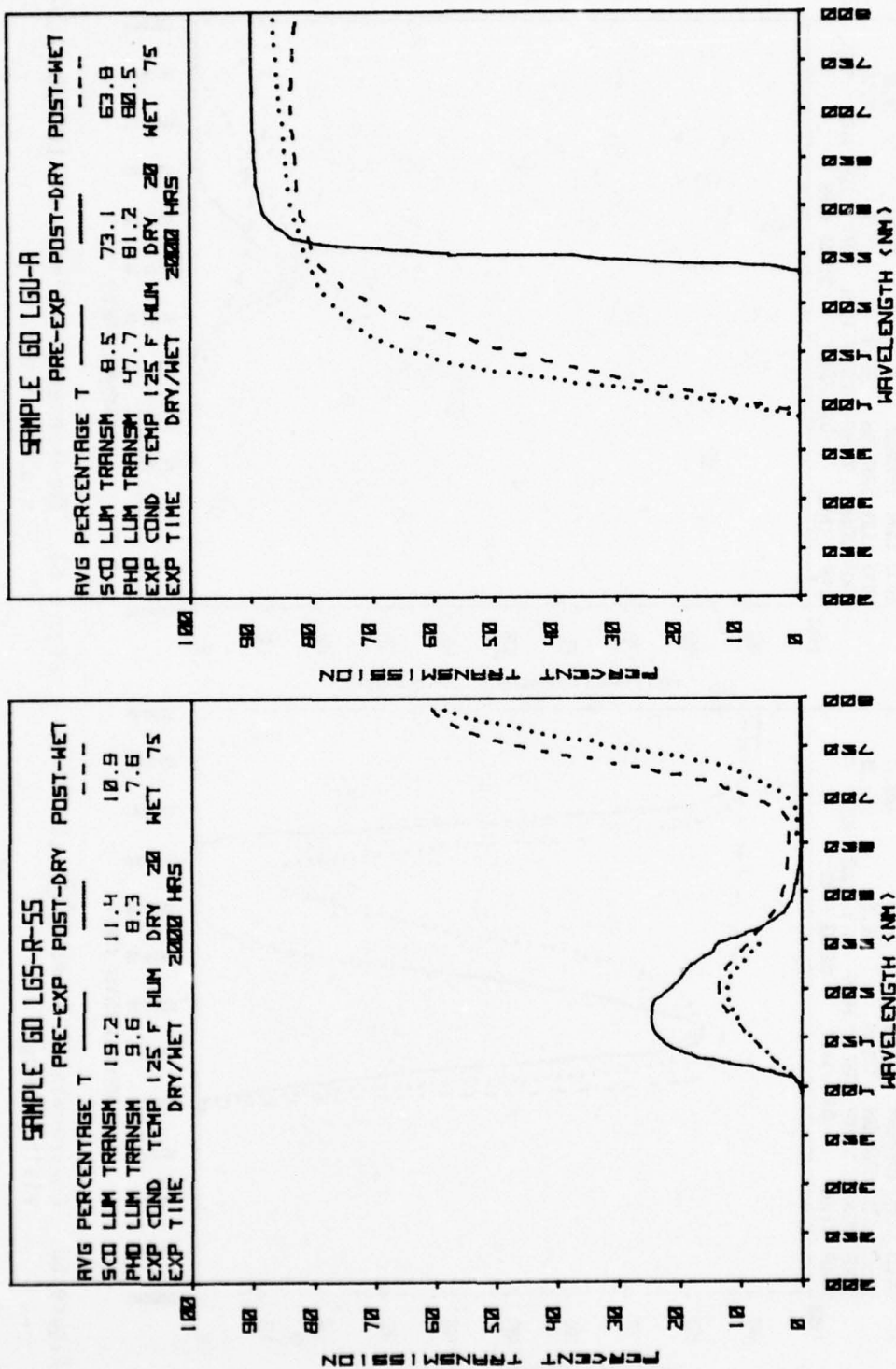


Figure 61. Environmental effects--60 LGU-A-UV-visible range.

Figure 60. Environmental effects--60 LGS-R-SS-UV-visible range.

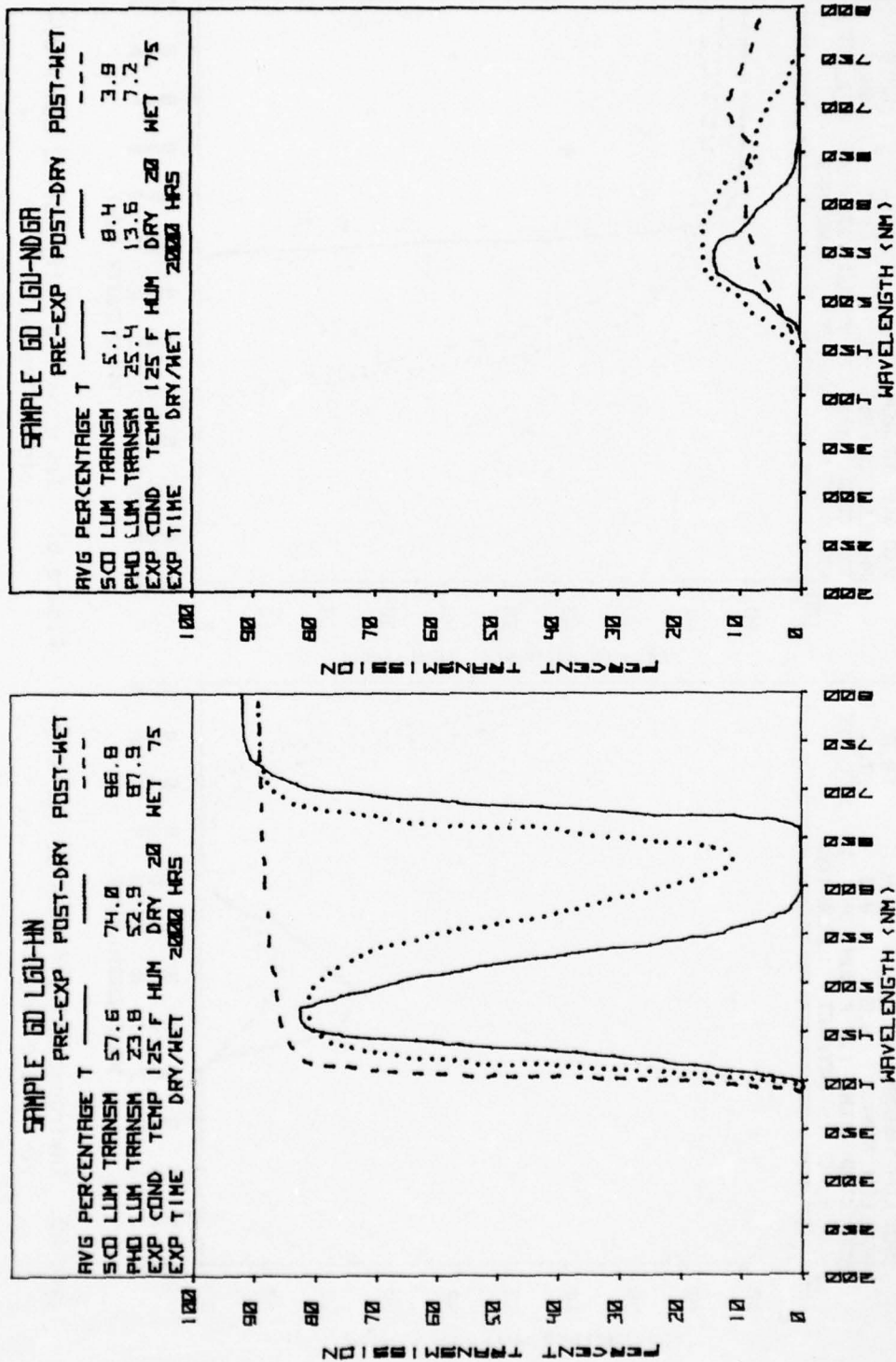


Figure 62. Environmental effects--G0 LGU-HN-UV-visible range.

Figure 63. Environmental effects--G0 LGU-NDGA-UV-visible range.

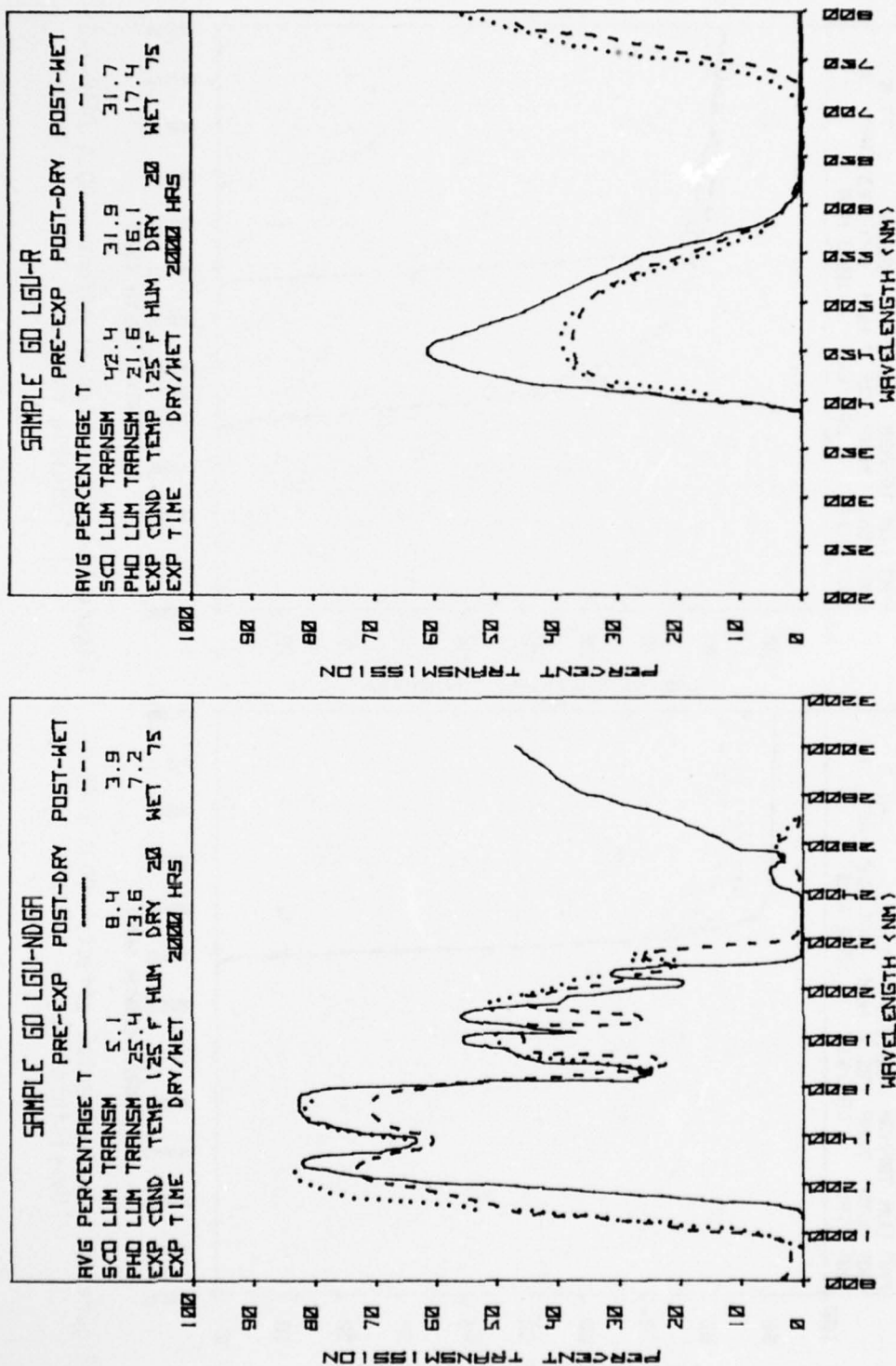


Figure 64. Environmental effects--G0 LGU-NDGA-NIR range.

Figure 65. Environmental effects--G0 LGU-R-UV-visible range.

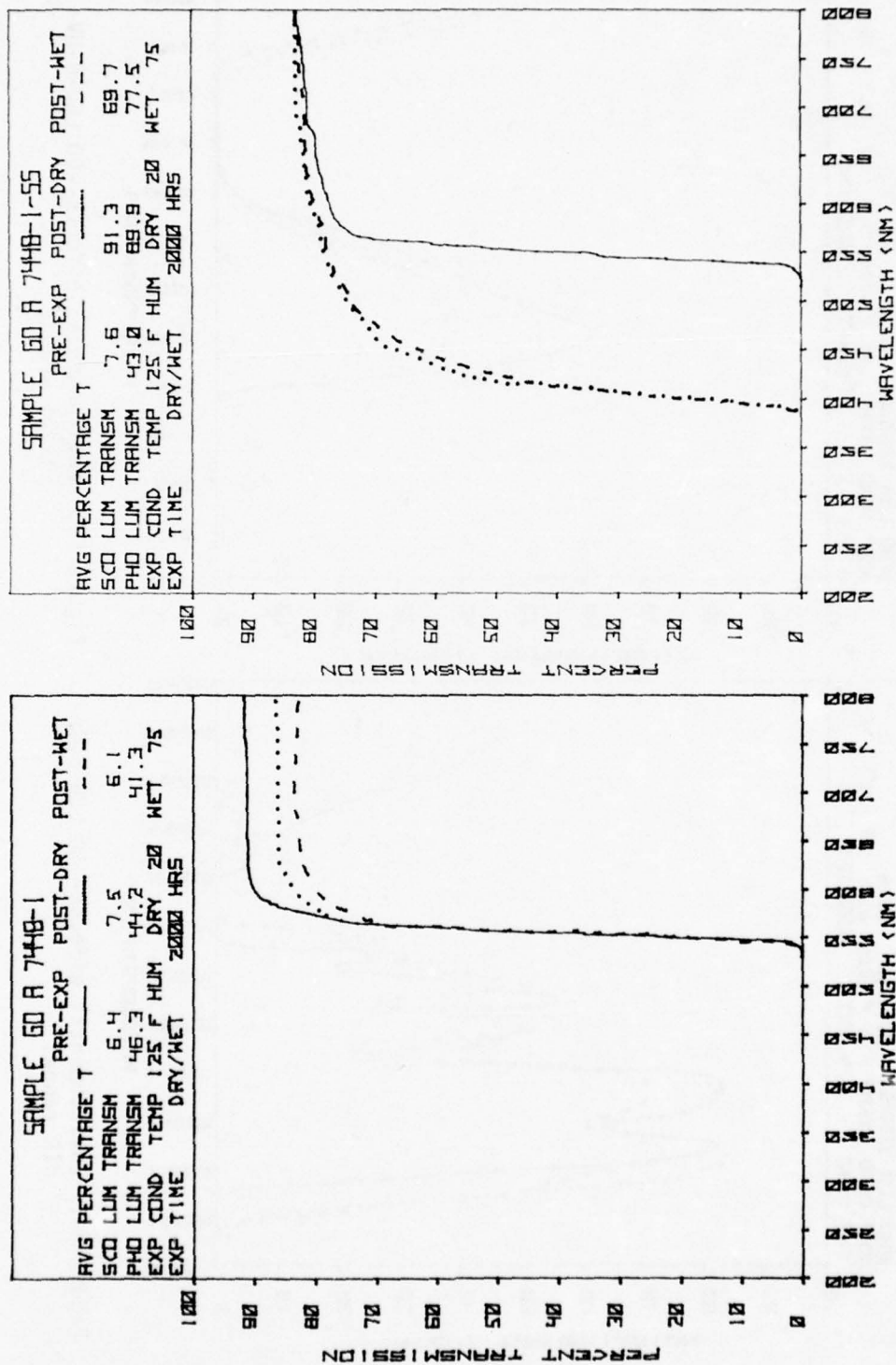


Figure 66. Environmental effects--G0 A 7448-1-UV-visible range.

Figure 67. Environmental effects--G0 A 7448-1-SS-UV-visible range.

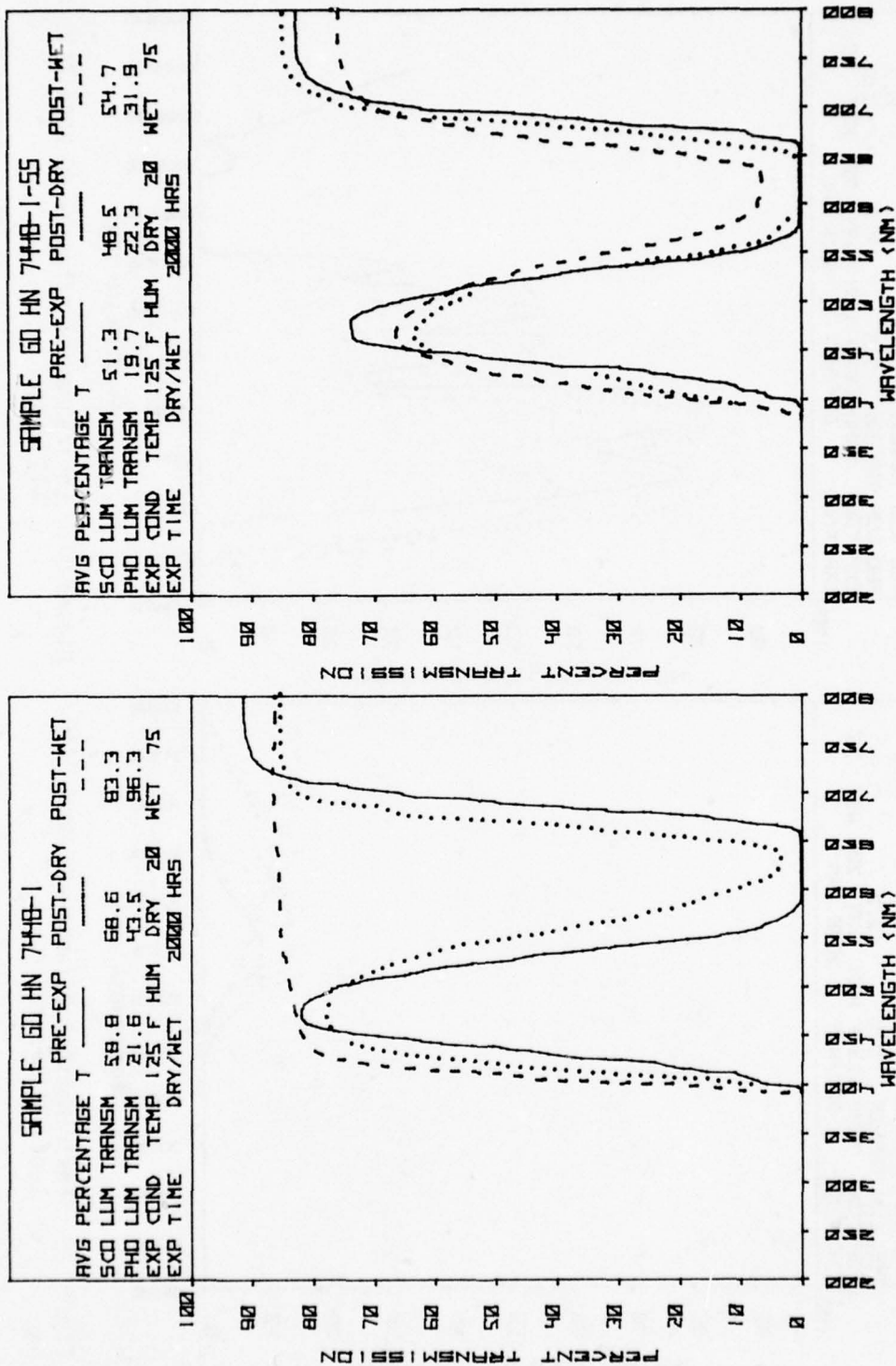


Figure 68. Environmental effects--G0 HN 7448-1-UV-visible range.

Figure 69. Environmental effects--G0 HN 7448-1-SS-UV-visible range.

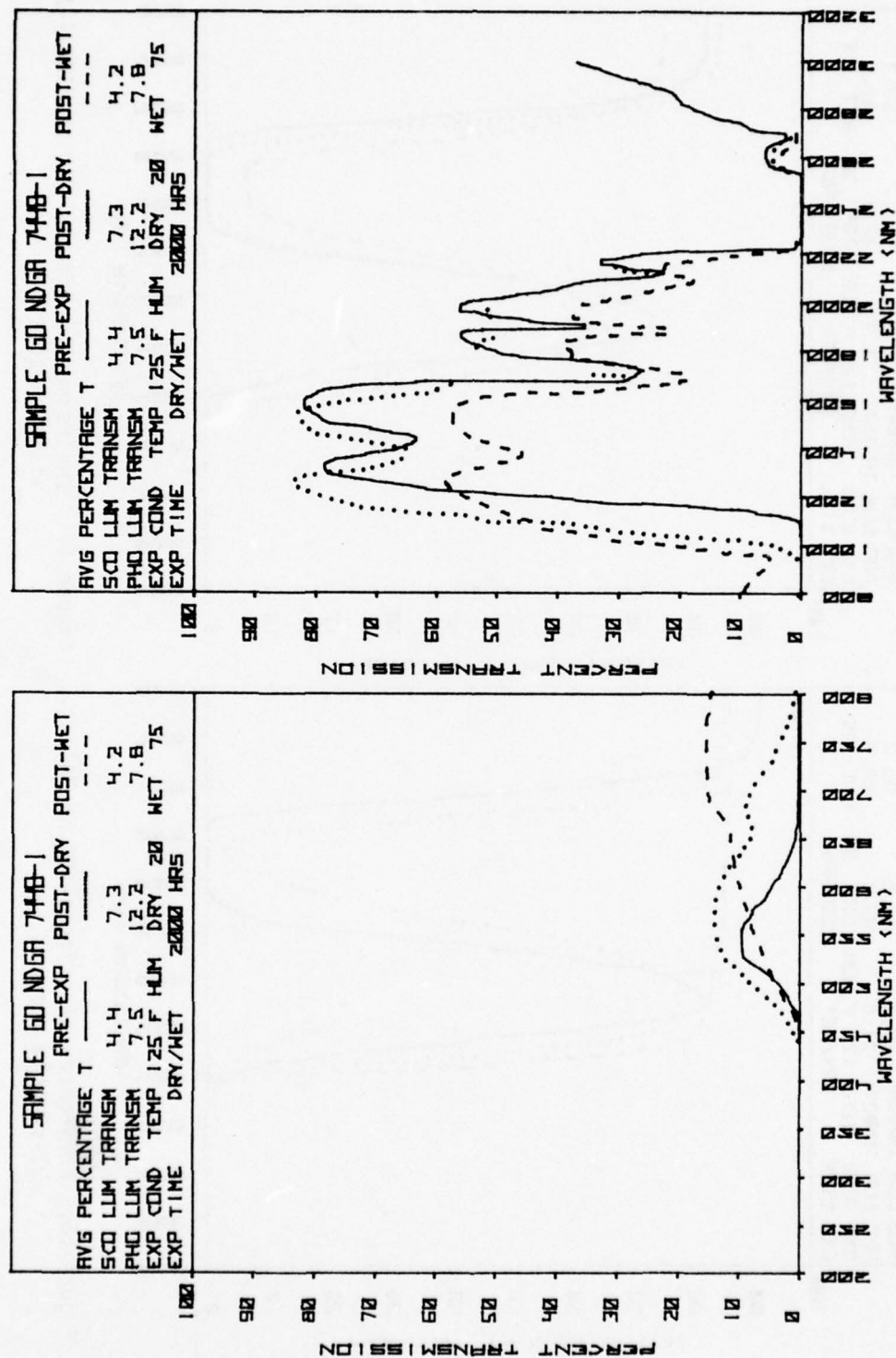


Figure 70. Environmental effects--G0 NDGA 7448-1-UV-visible range.

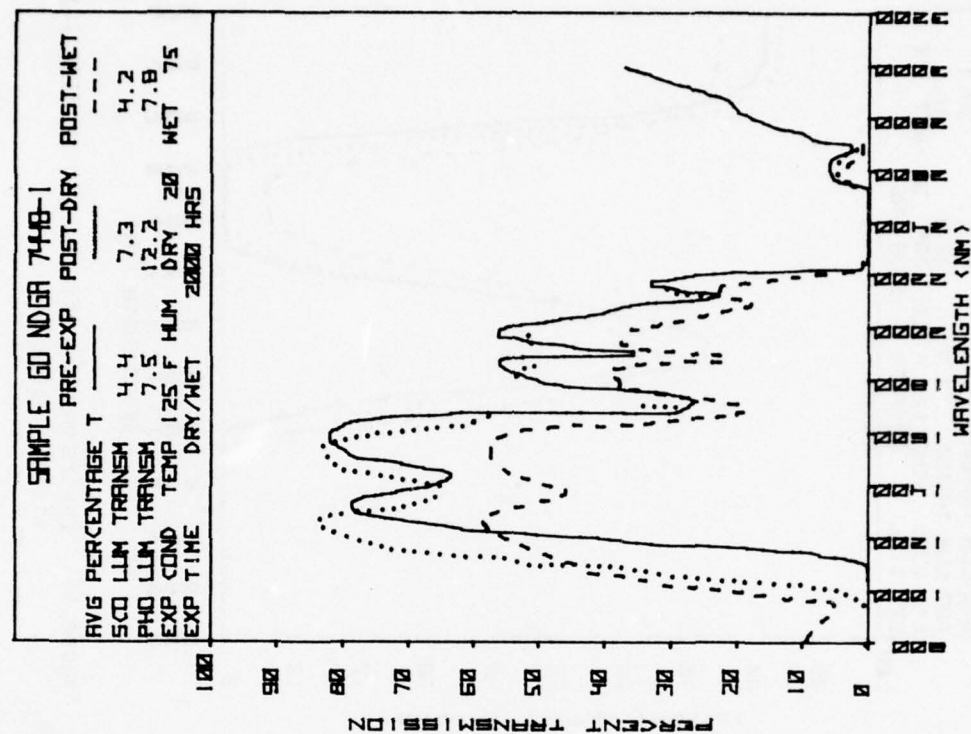


Figure 71. Environmental effects--G0 NDGA 7448-1-NIR range.

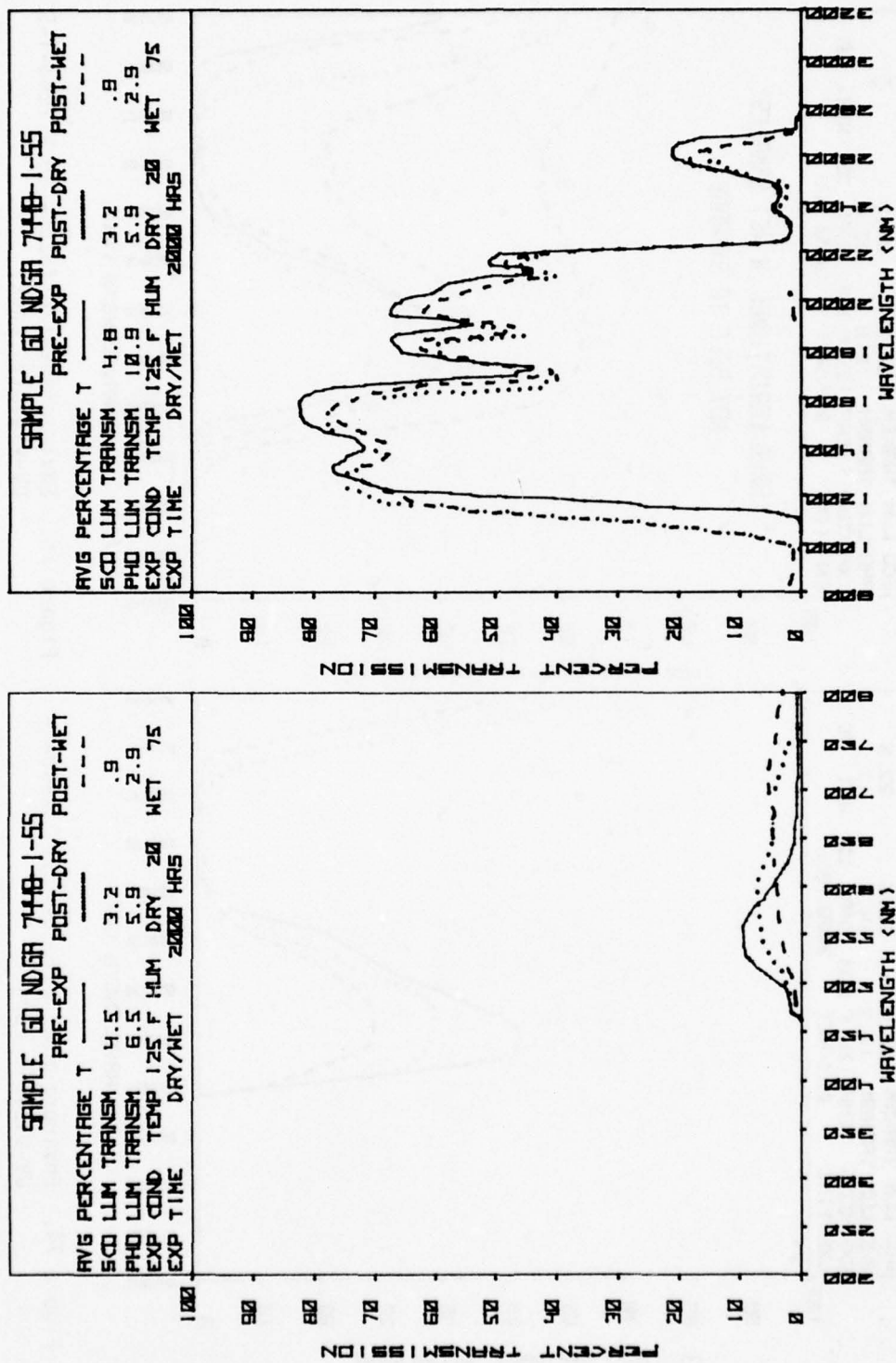


Figure 72. Environmental effects--GO NDGA 7448-1-SS-UV-visible range.

Figure 73. Environmental effects--GO NDGA 7448-1-SS-NIR range.

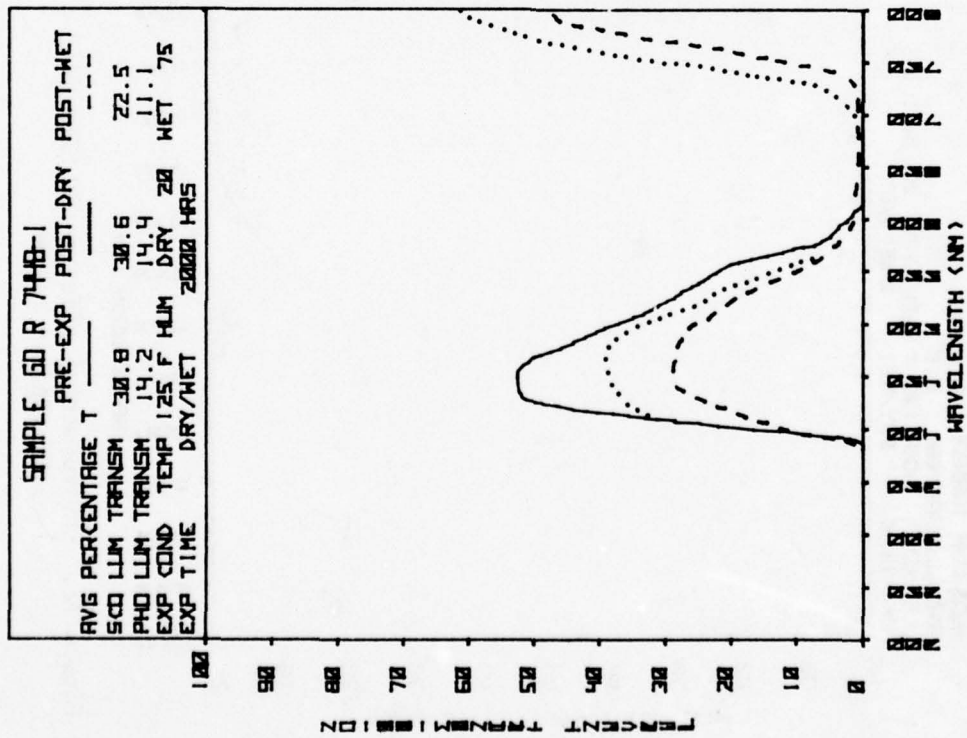


Figure 74. Environmental effects--G0 R 7448-1-UV-visible range.

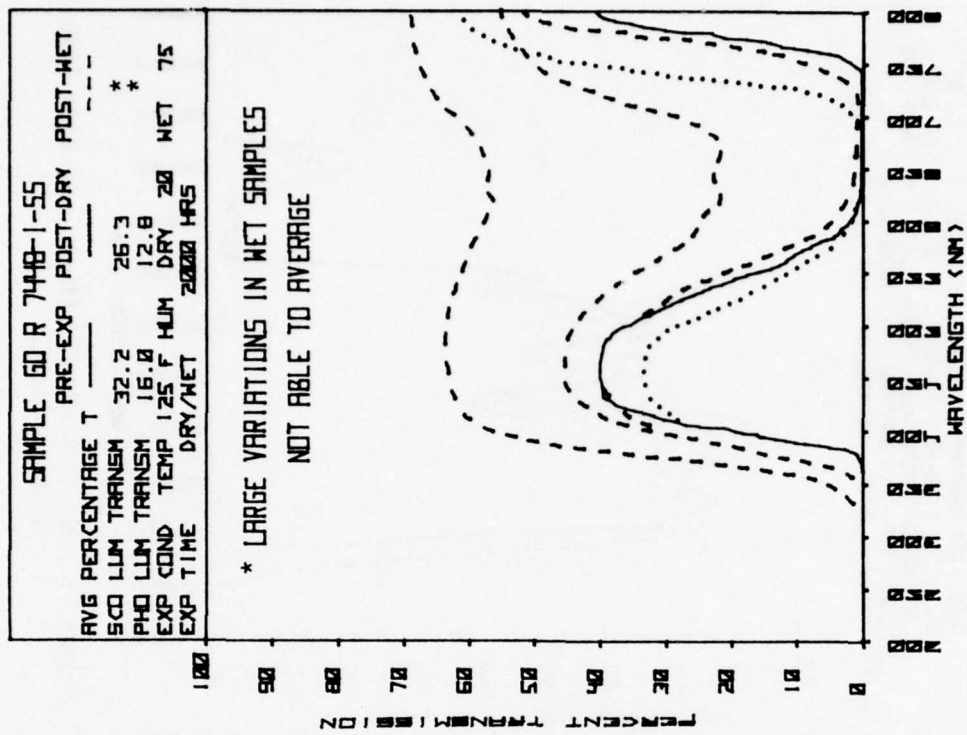


Figure 75. Environmental effects--G0 R 7448-1-SS-UV-visible range.

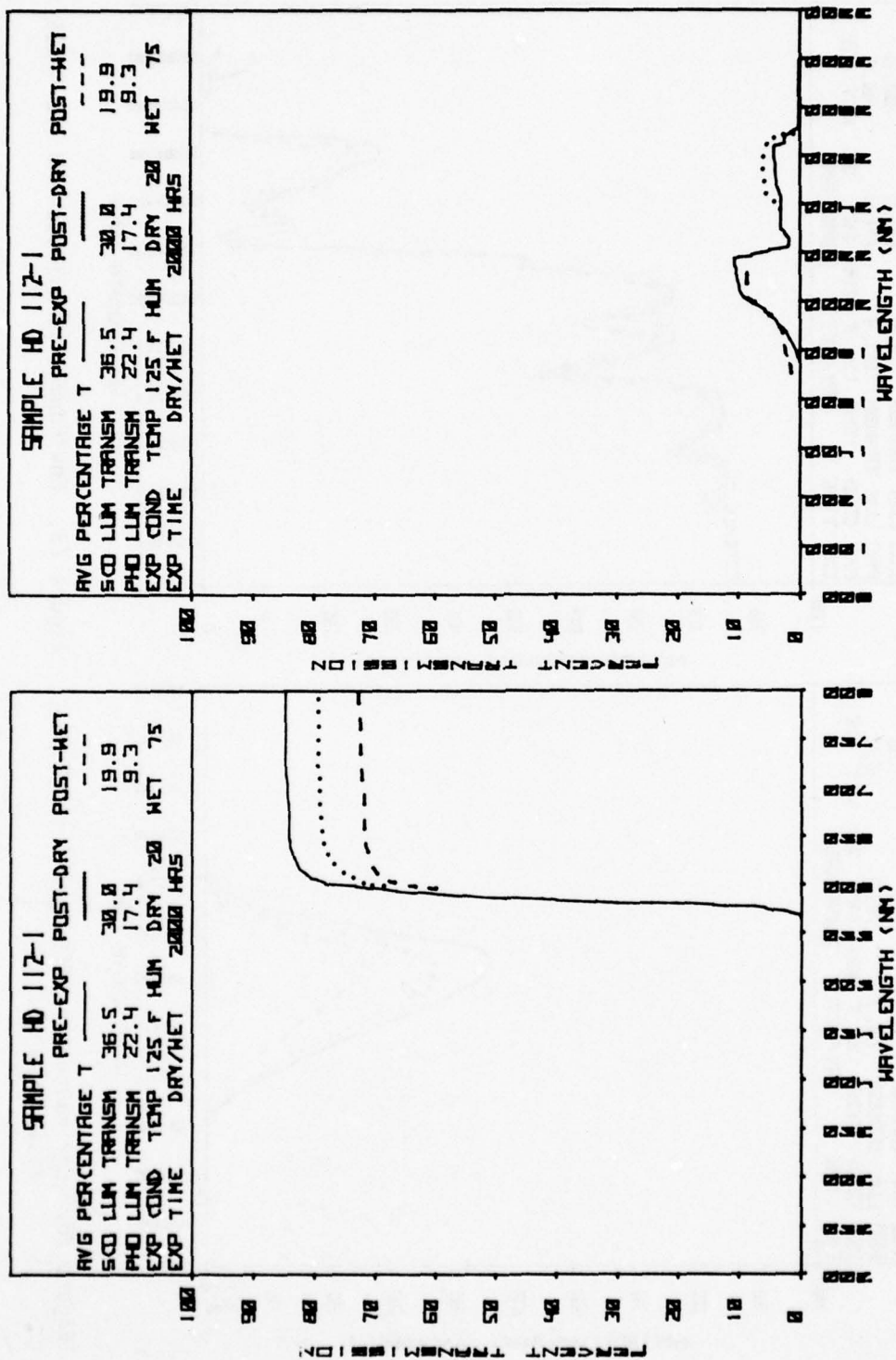


Figure 76. Environmental effects--HD 112-1-UV-visible range.

Figure 77. Environmental effects--HD 112-1-NIR range.

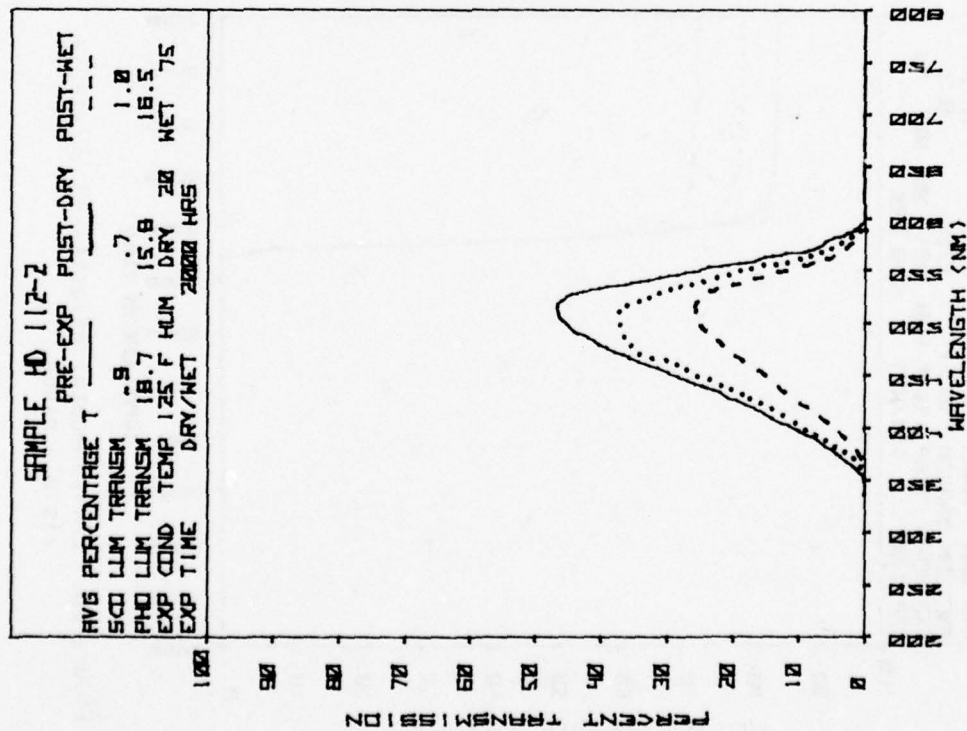


Figure 78. Environmental effects--HD 112-2-UV-visible range.

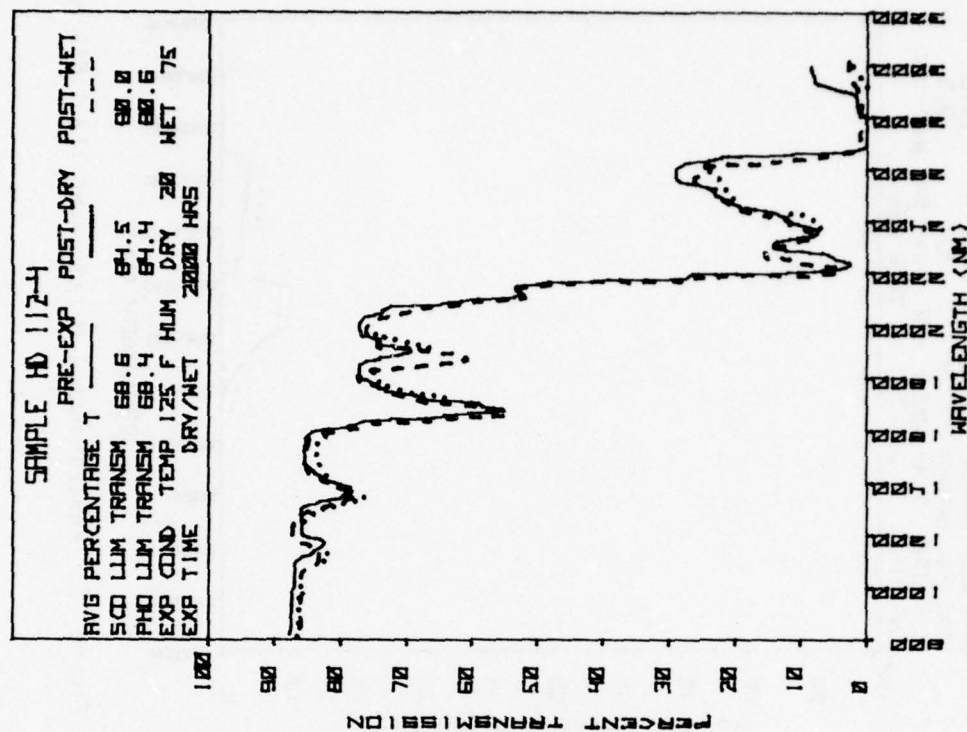


Figure 79. Environmental effects--HD 112-4-NIR range.

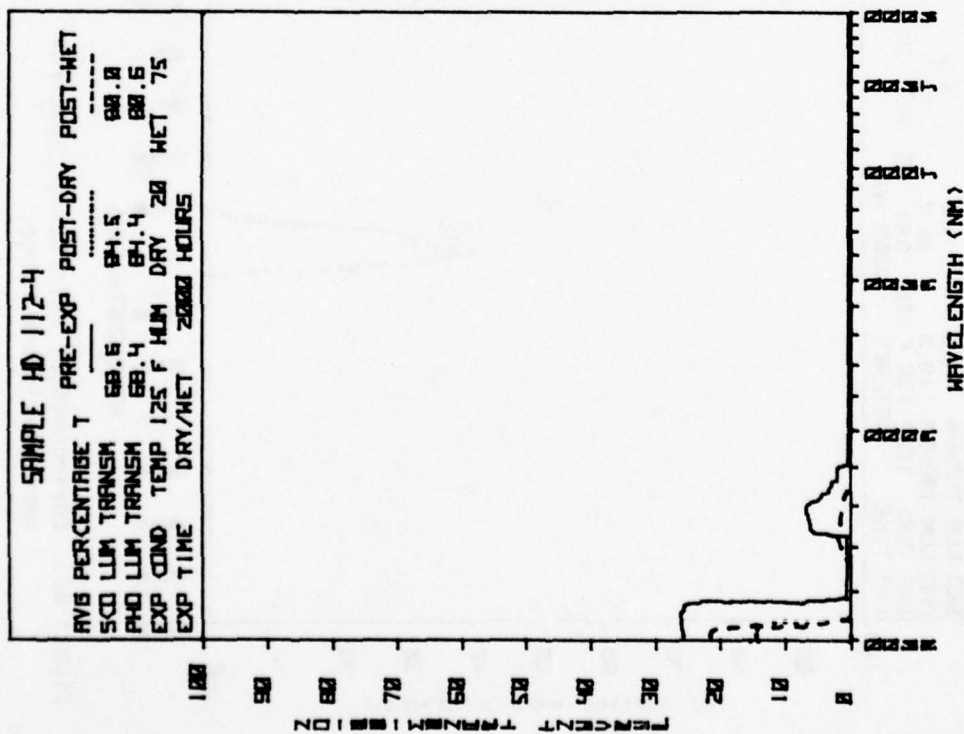


Figure 80. Environmental effects--HD 112-4-IR range.

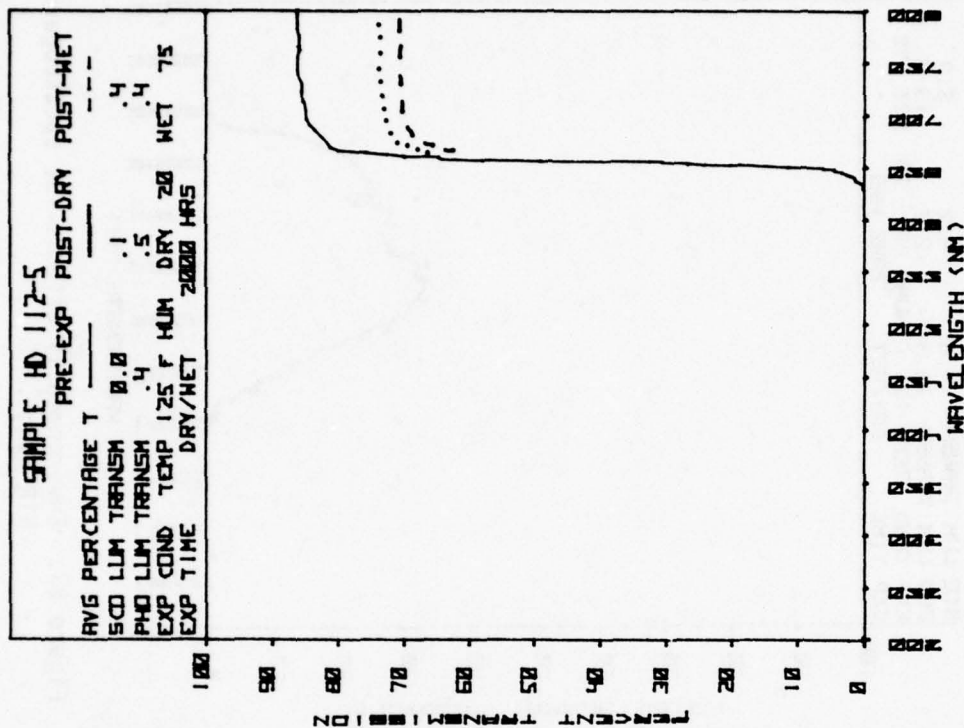


Figure 81. Environmental effects--HD 112-5-UV-visible range.

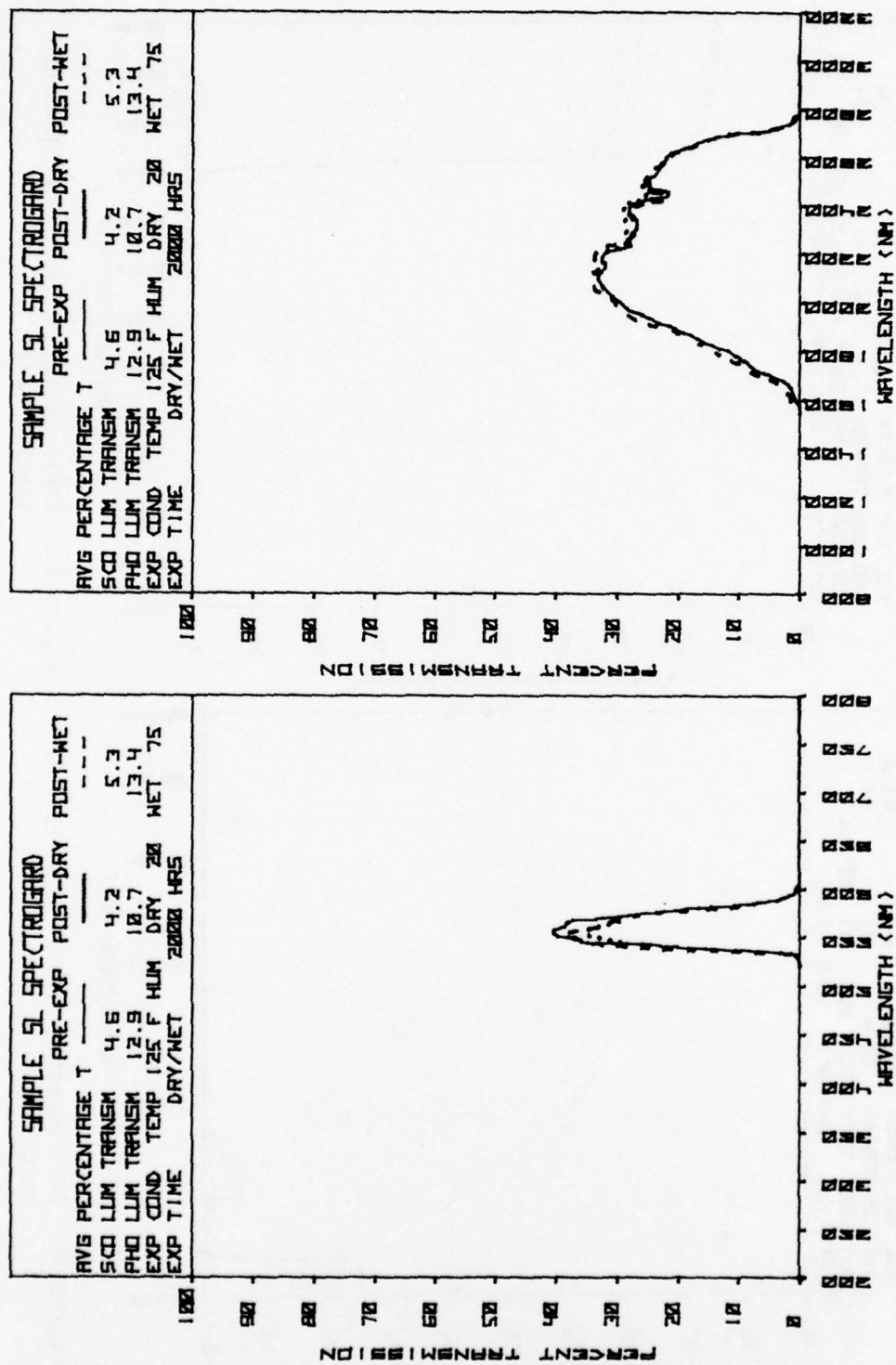


Figure 82. Environmental effects--SL spectrograph-UV-visible range.

Figure 83. Environmental effects--SL spectrograph-NIR range.

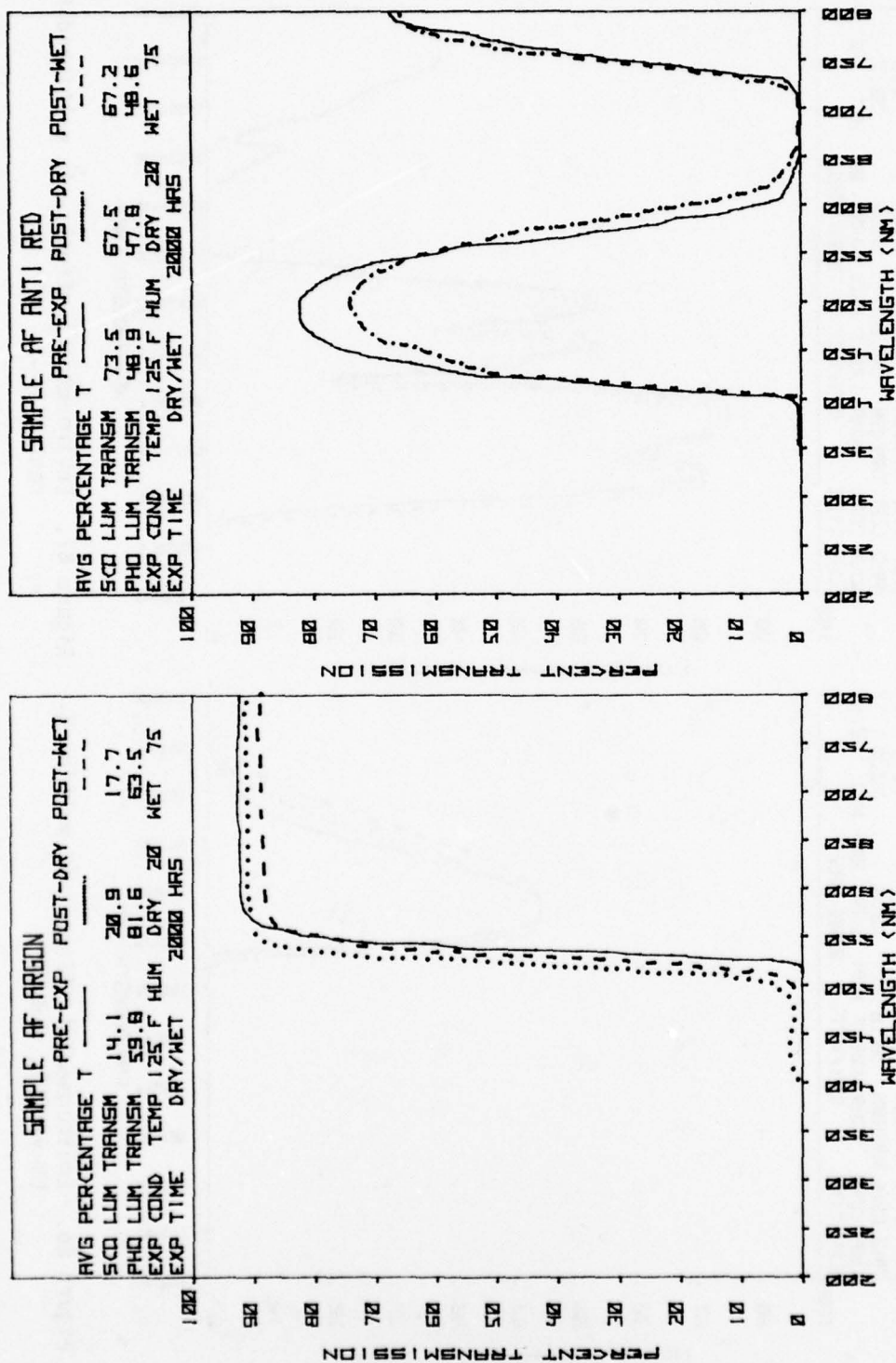


Figure 84. Environmental effects--AF argon-UV-visible range.

Figure 85. Environmental effects--AF anti-red-UV-visible range.

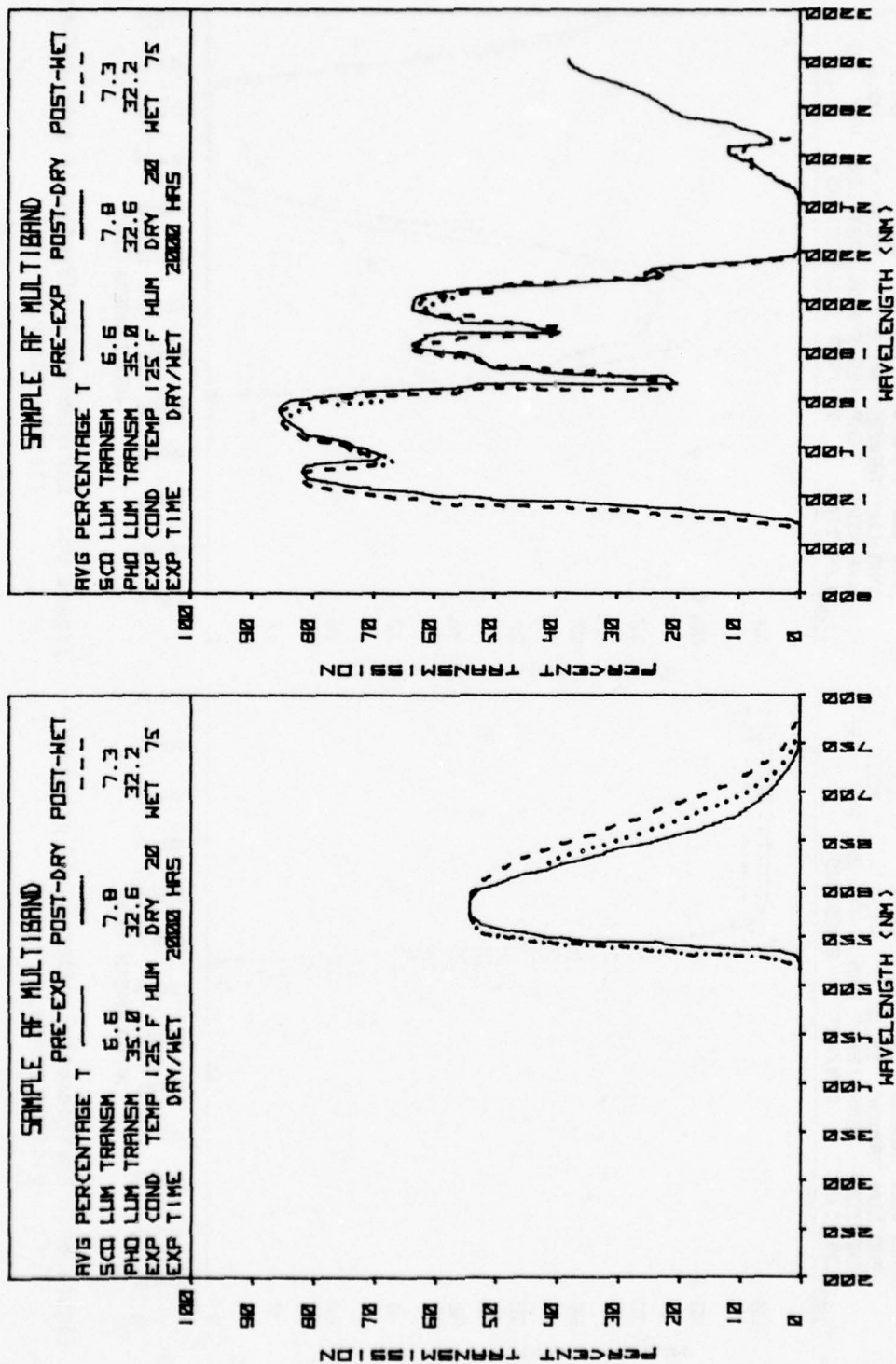


Figure 86. Environmental effects--AF multiband-UV-visible range.

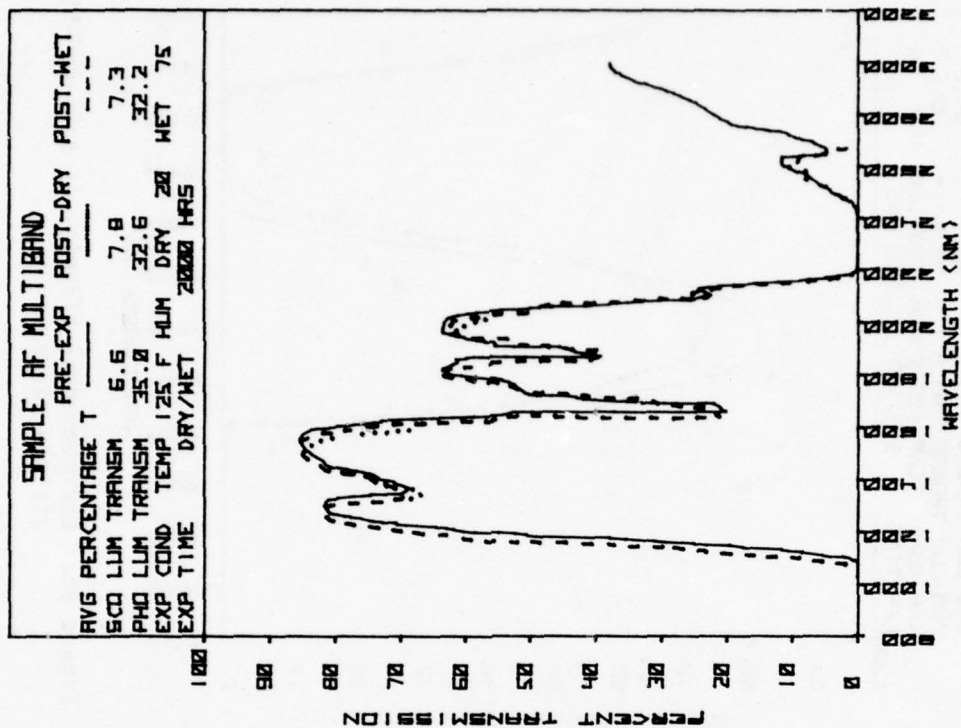


Figure 87. Environmental effects--AF multiband-NIR range.

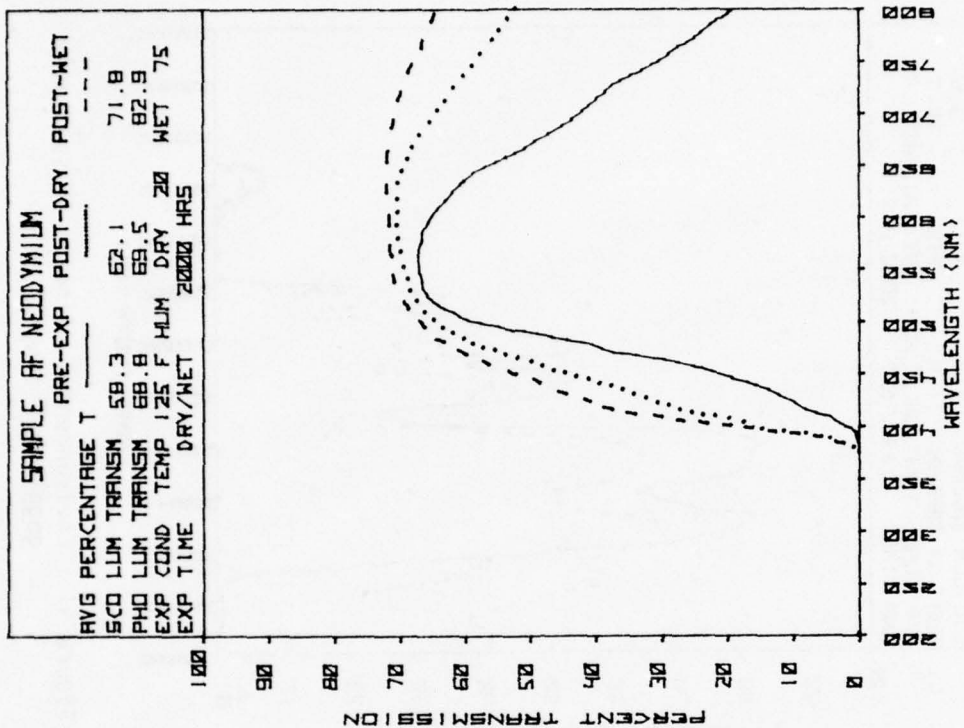


Figure 89. Environmental effects--AF neodymium-UV-visible range.

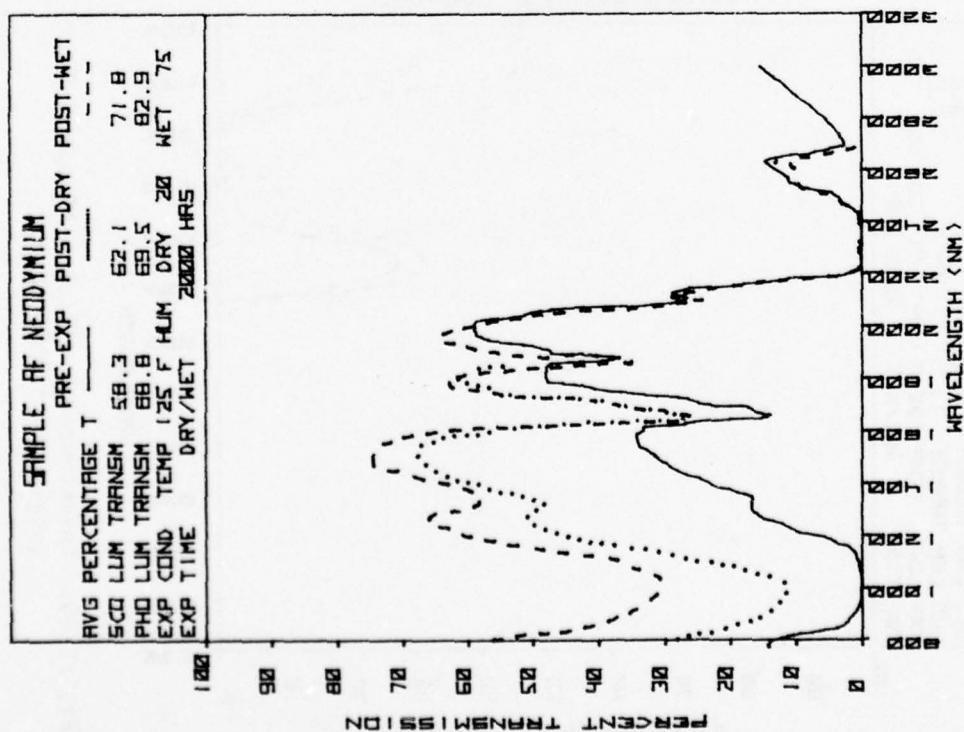
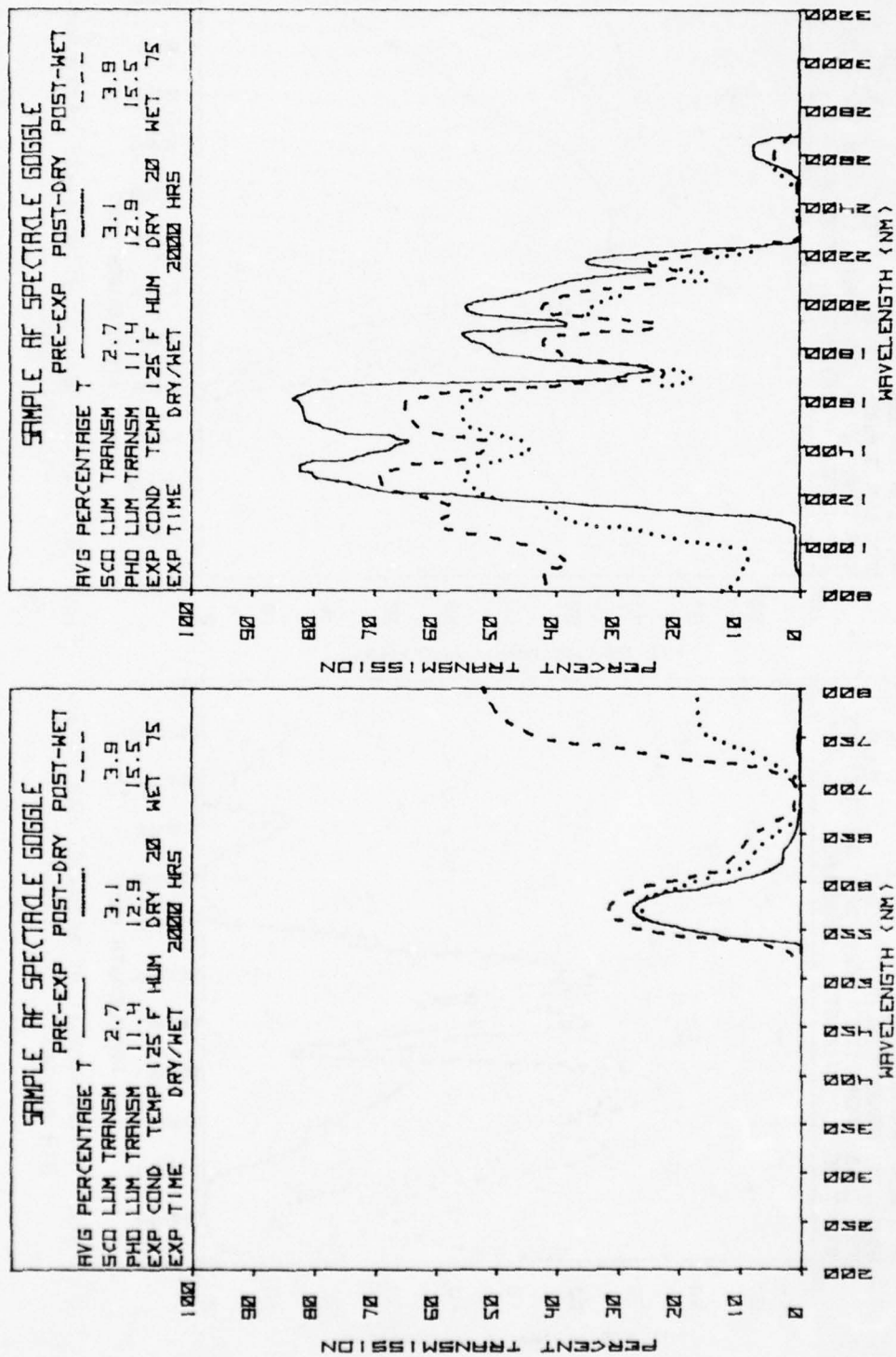


Figure 88. Environmental effects--AF neodymium-NIR range.



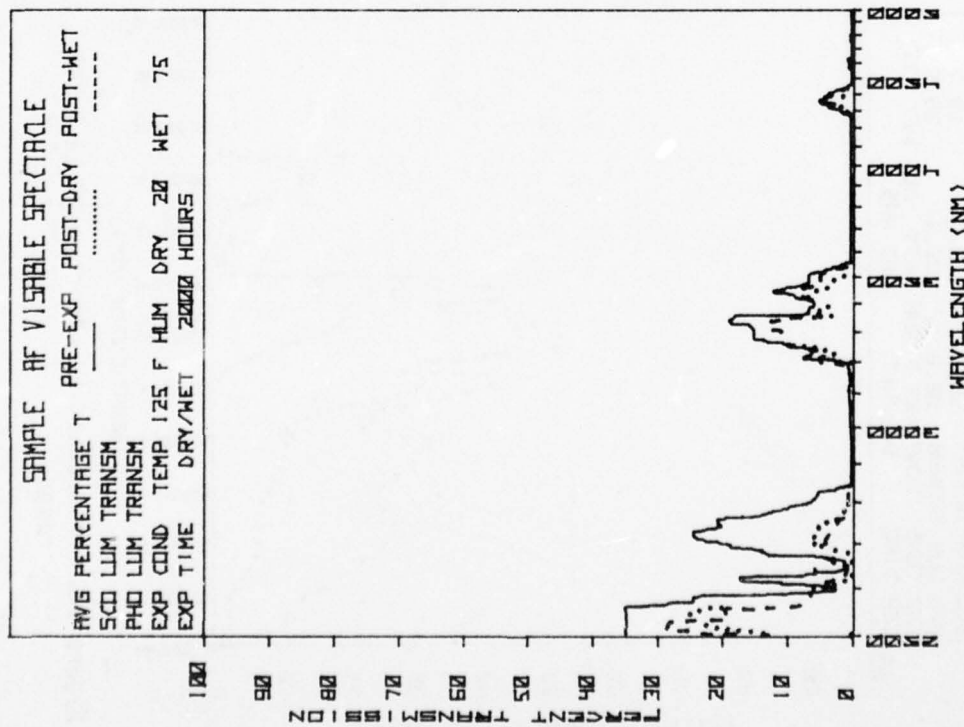


Figure 92. Environmental effects--AF visible spectacle-IR range.

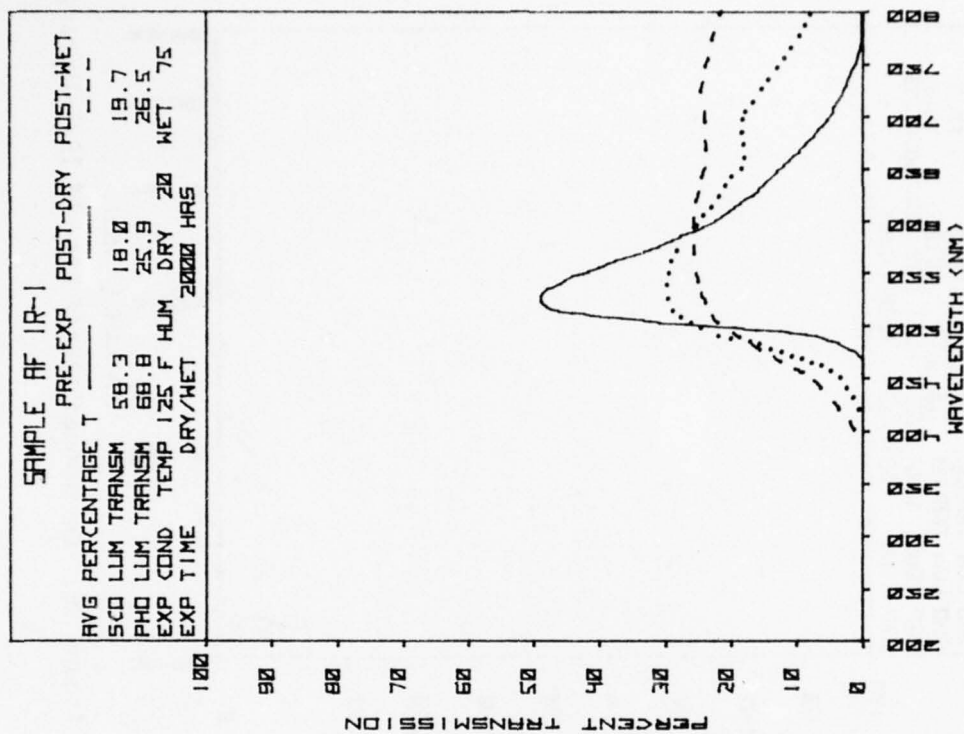


Figure 93. Environmental effects--AF IR-1-UV-visible range.

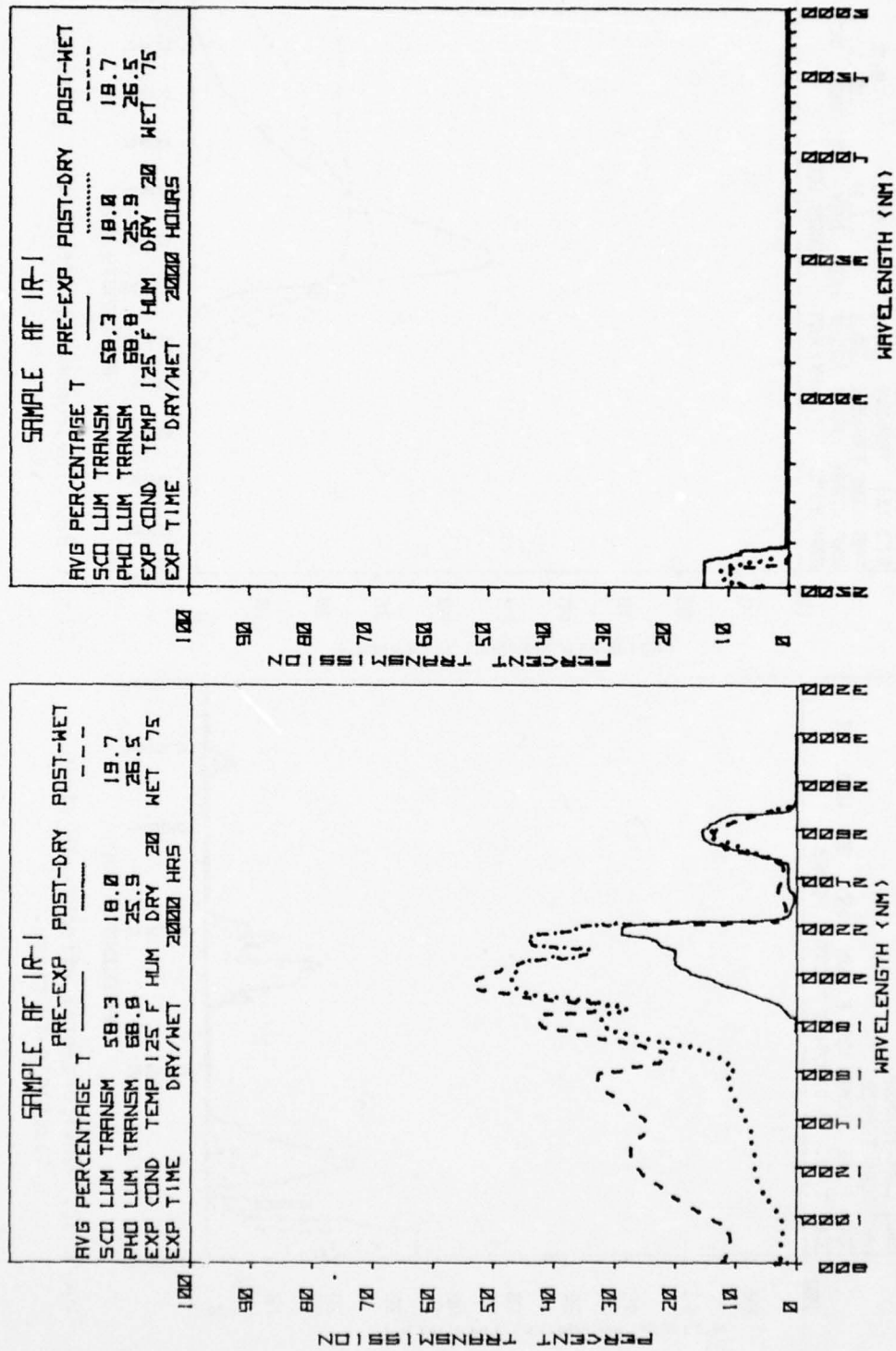


Figure 94. Environmental effects--AF IR-1-NIR range.

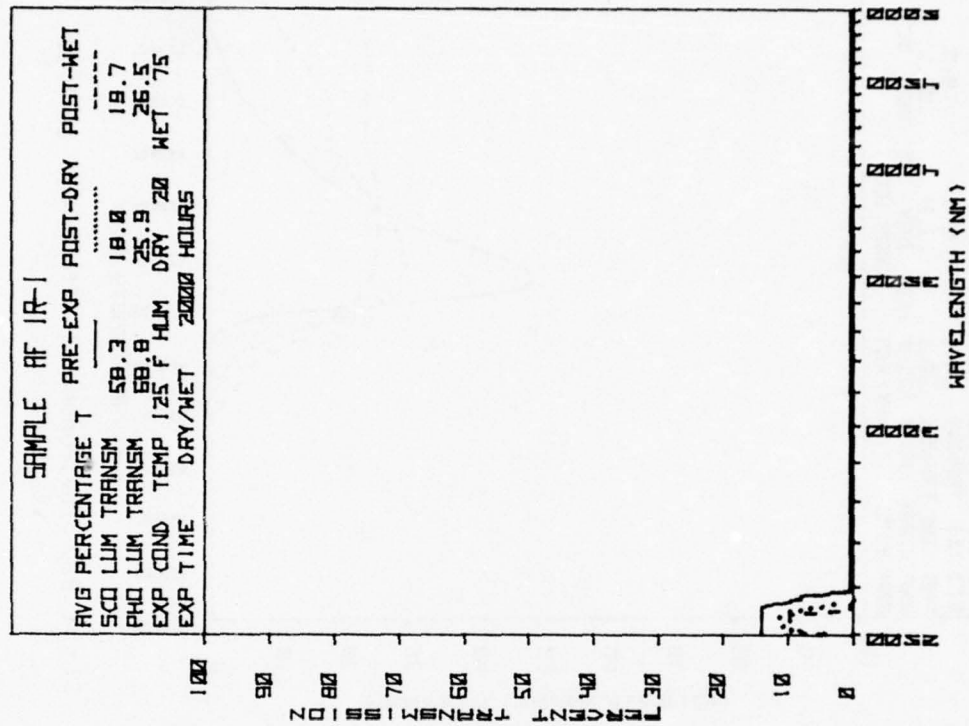


Figure 95. Environmental effects--AF IR-1-IR range.

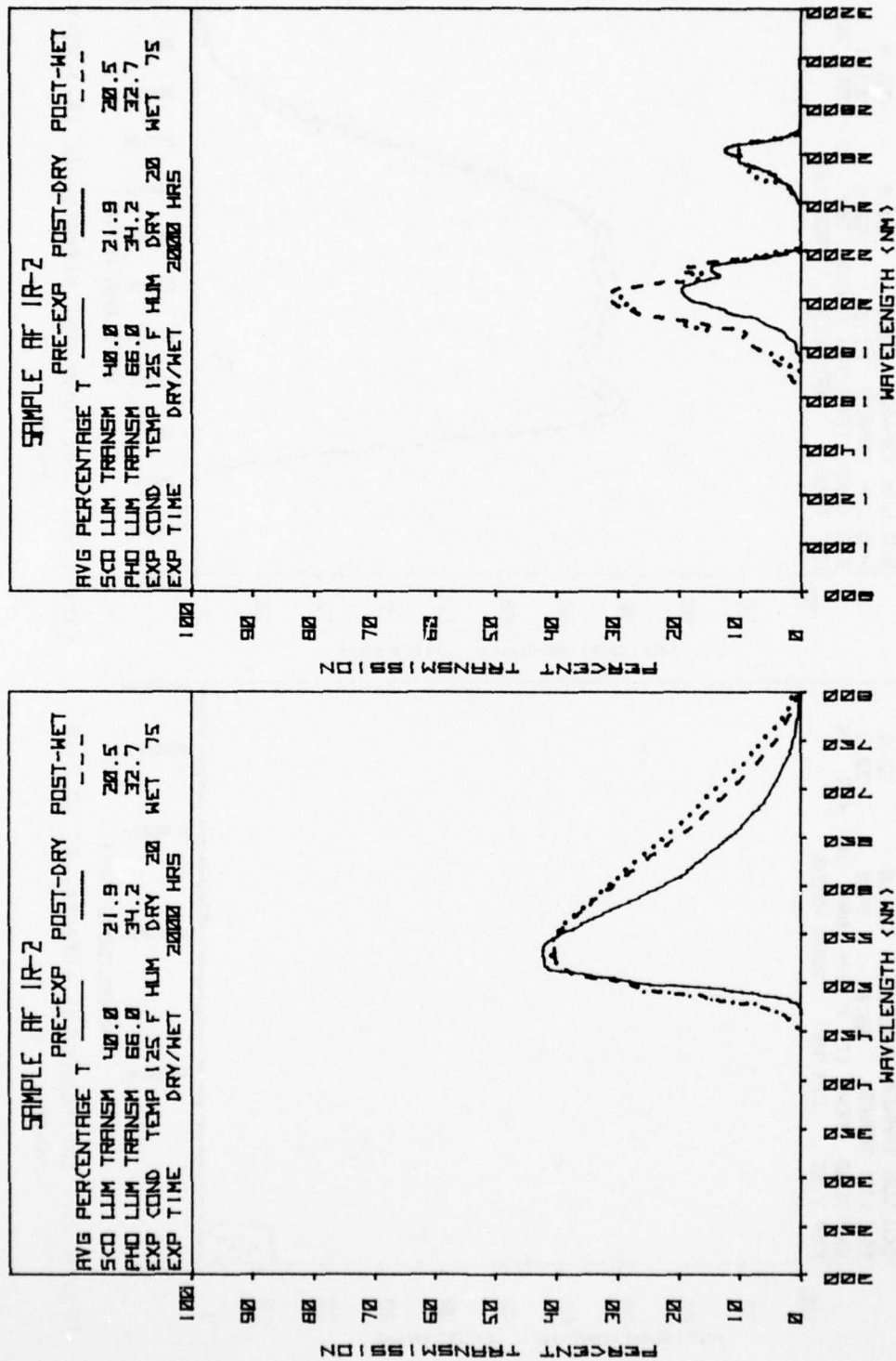


Figure 96. Environmental effects--AF IR-2-UV-visible range.

Figure 97. Environmental effects--AF IR-2-NIR range.

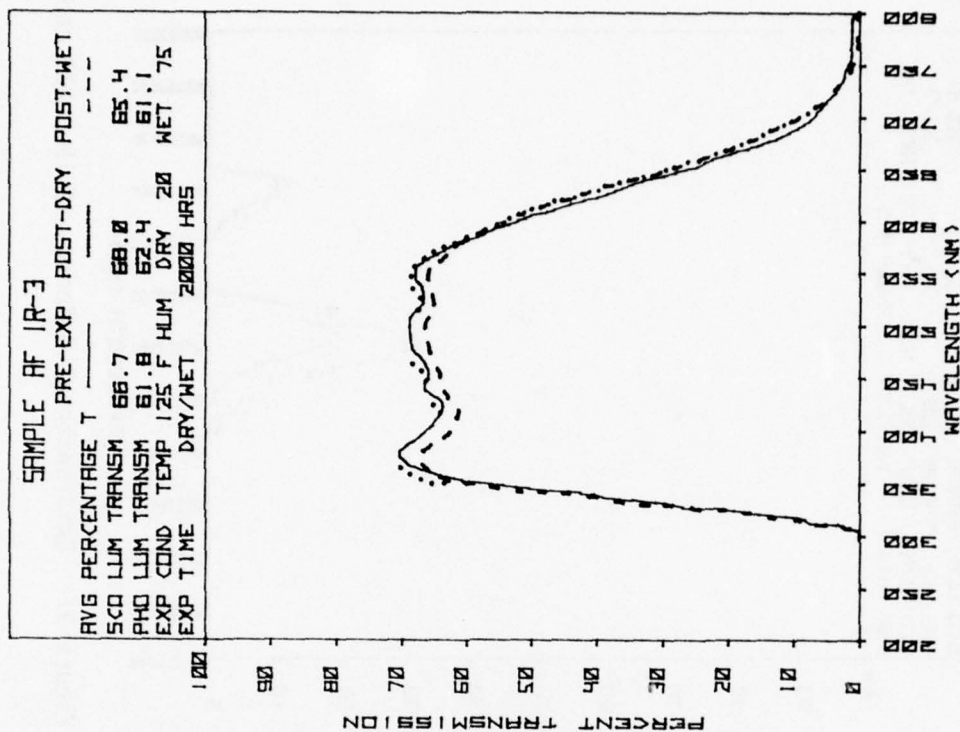


Figure 99. Environmental effects--AF IR-3-UV-visible range.

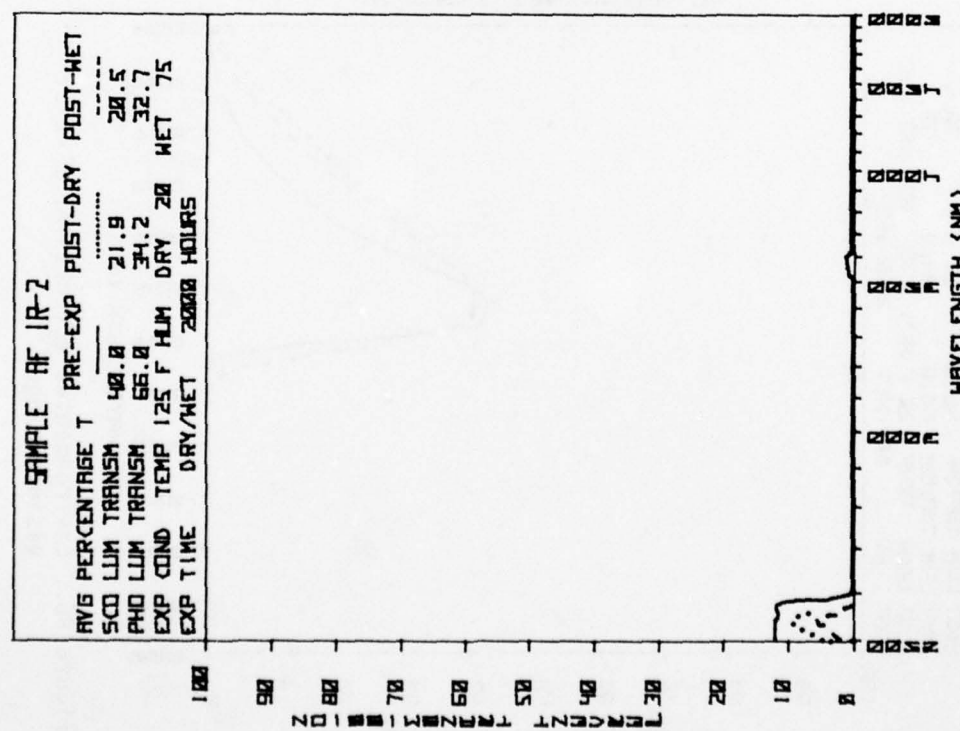


Figure 98. Environmental effects--AF IR-2-IR range.

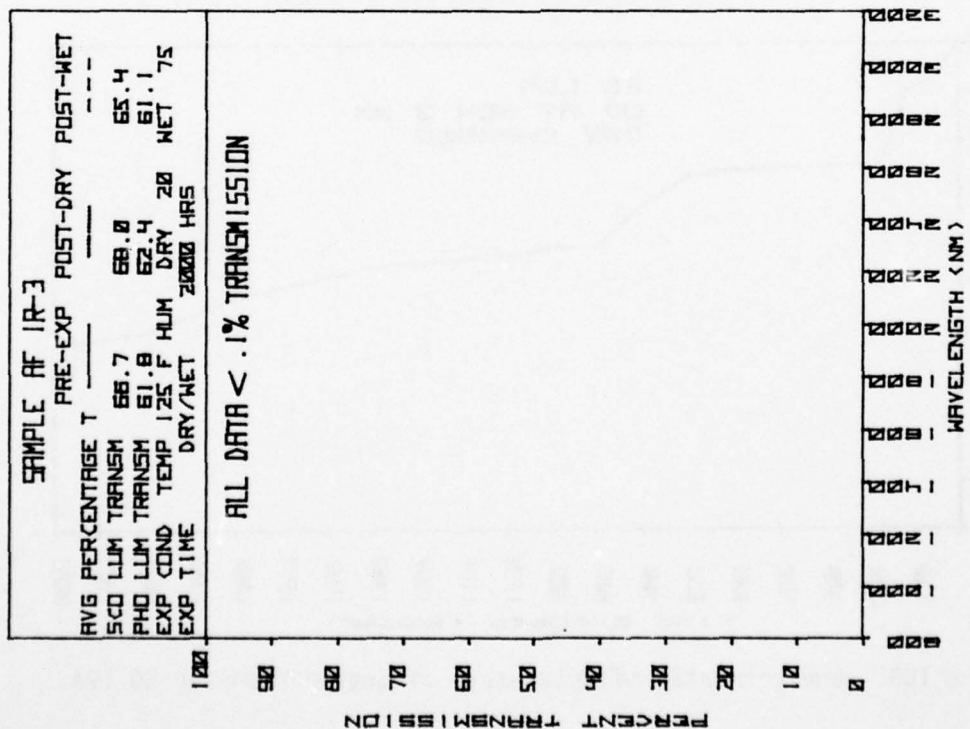


Figure 100. Environmental effects--AF IR-3-NIR range.

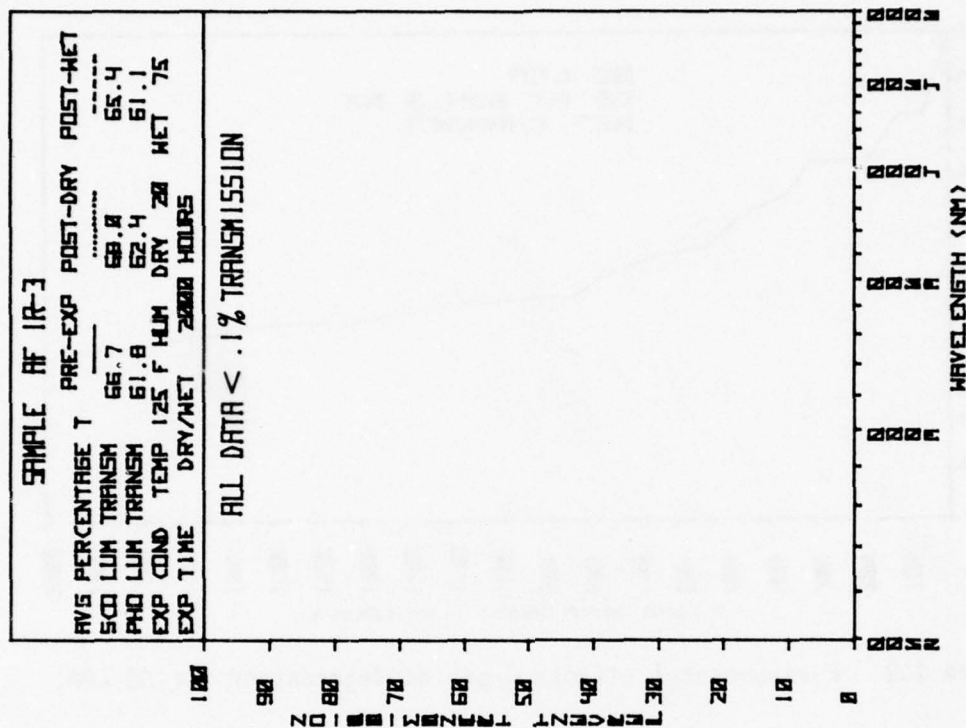


Figure 101. Environmental effects--AF IR-3-IR range.

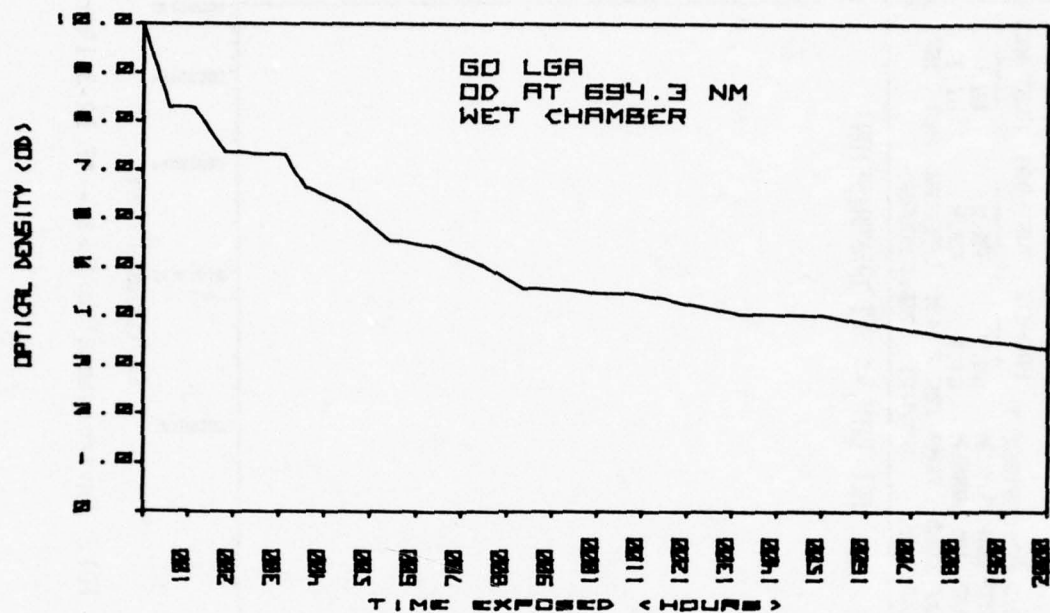


Figure 102. Environmental effects--rate of degradation for GO LGA.

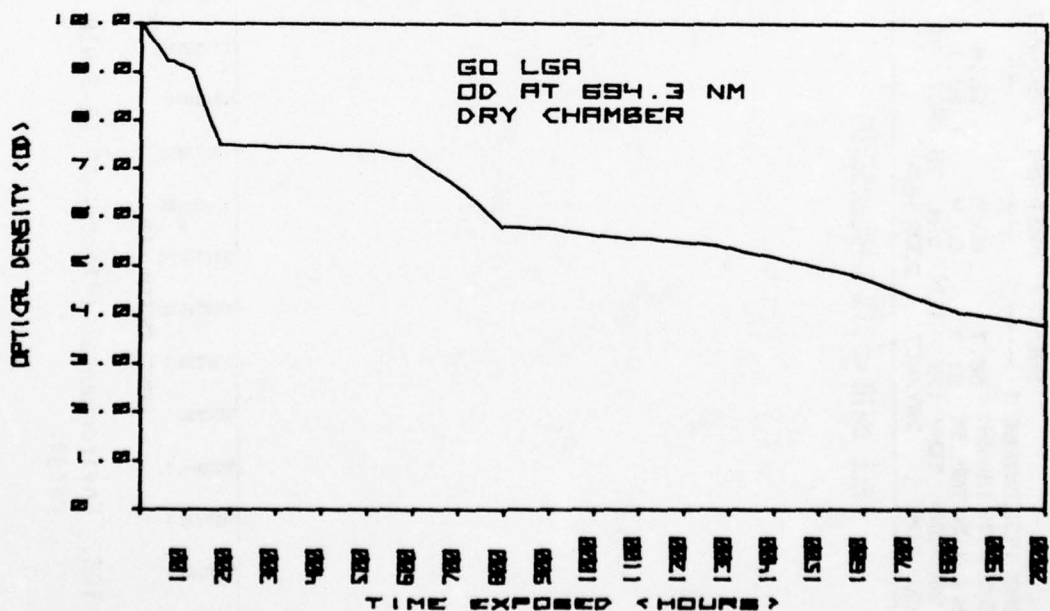


Figure 103. Environmental effects--rate of degradation for GO LGA.

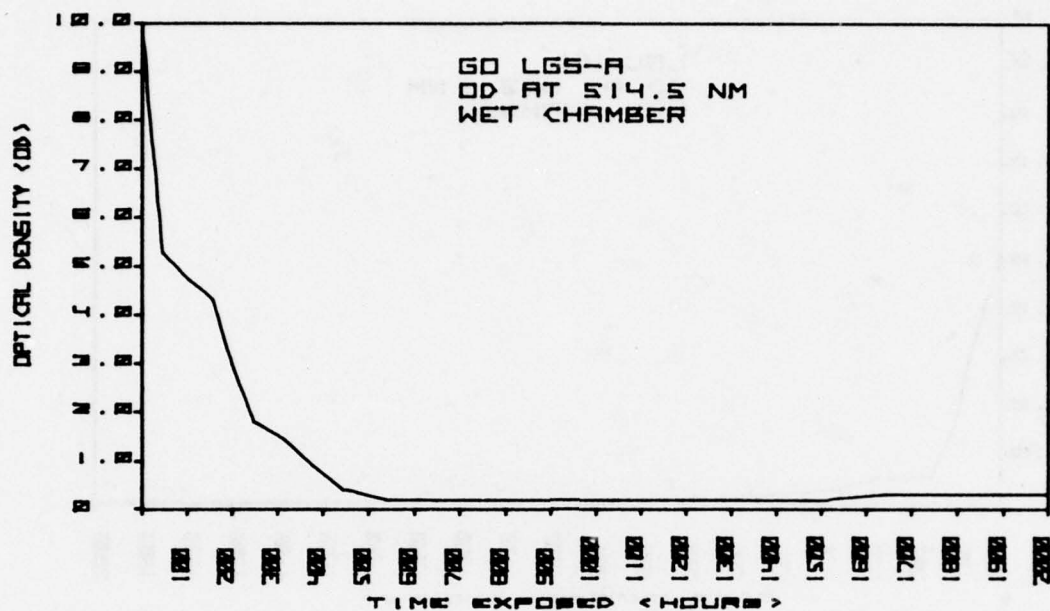


Figure 104. Environmental effects--rate of degradation for GO LGS-A.

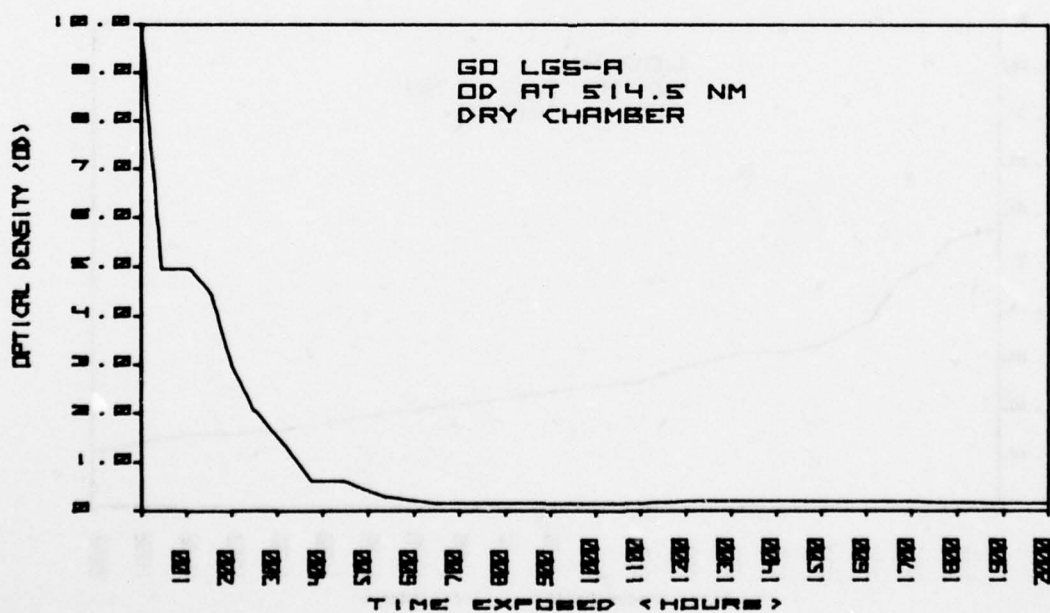


Figure 105. Environmental effects--rate of degradation for GO LGS-A.

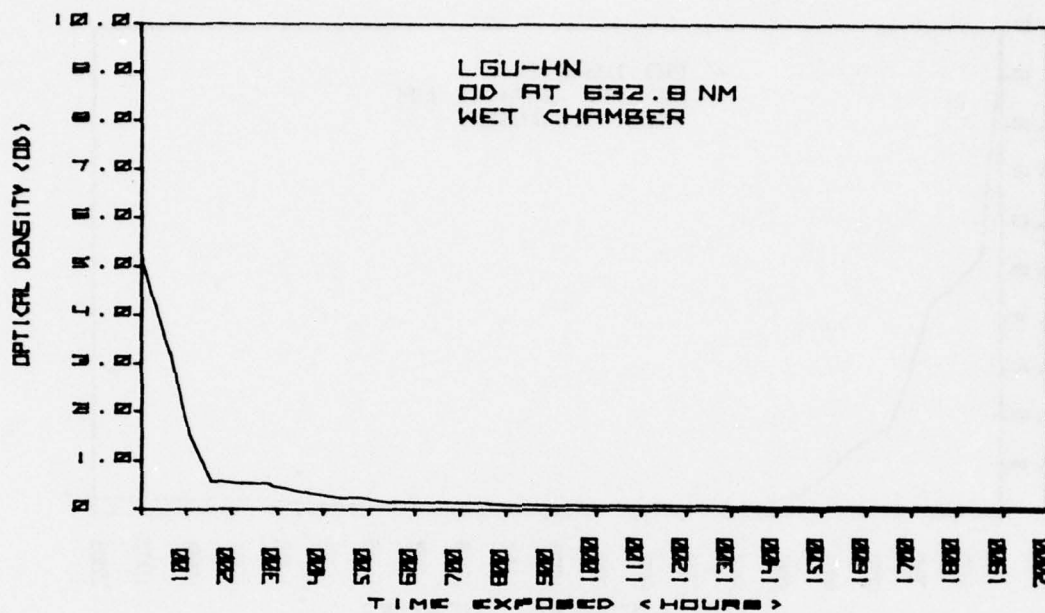


Figure 106. Environmental effects--rate of degradation for GO LGU-HN.

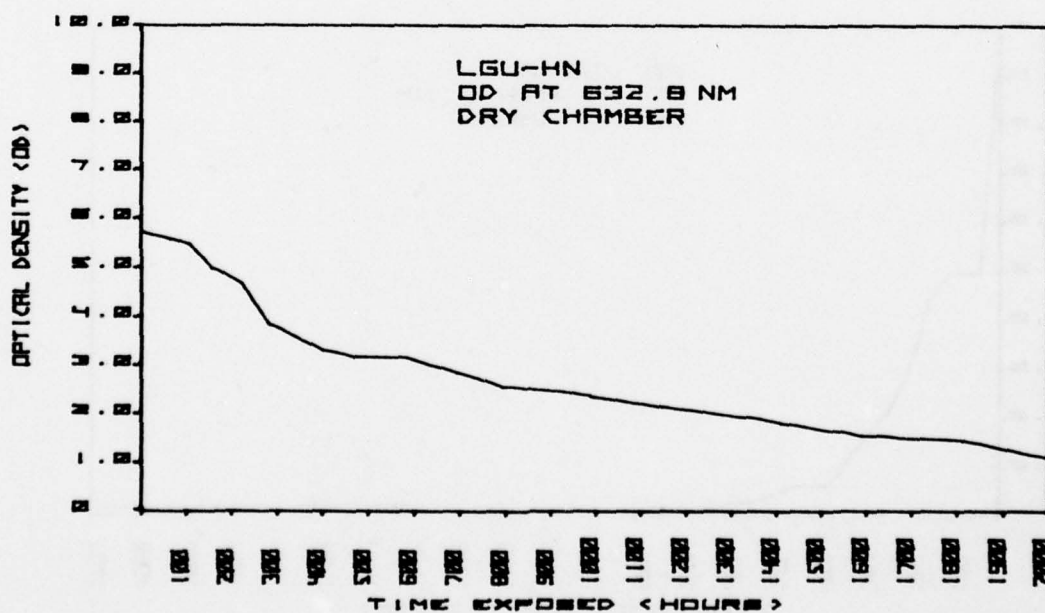


Figure 107. Environmental effects--rate of degradation for GO LGU-HN.

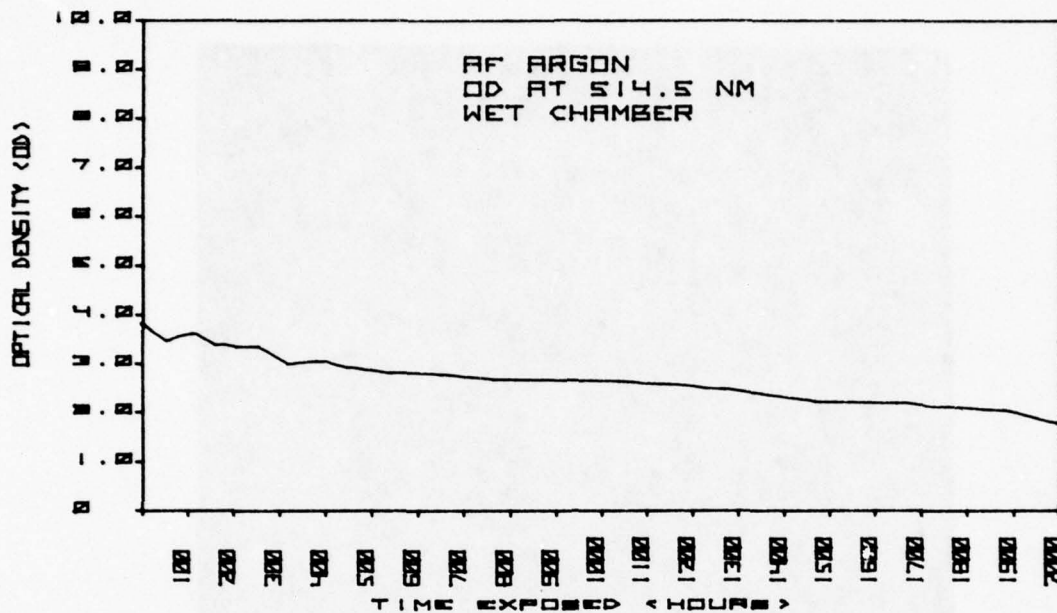


Figure 108. Environmental effects--rate of degradation for AF argon.

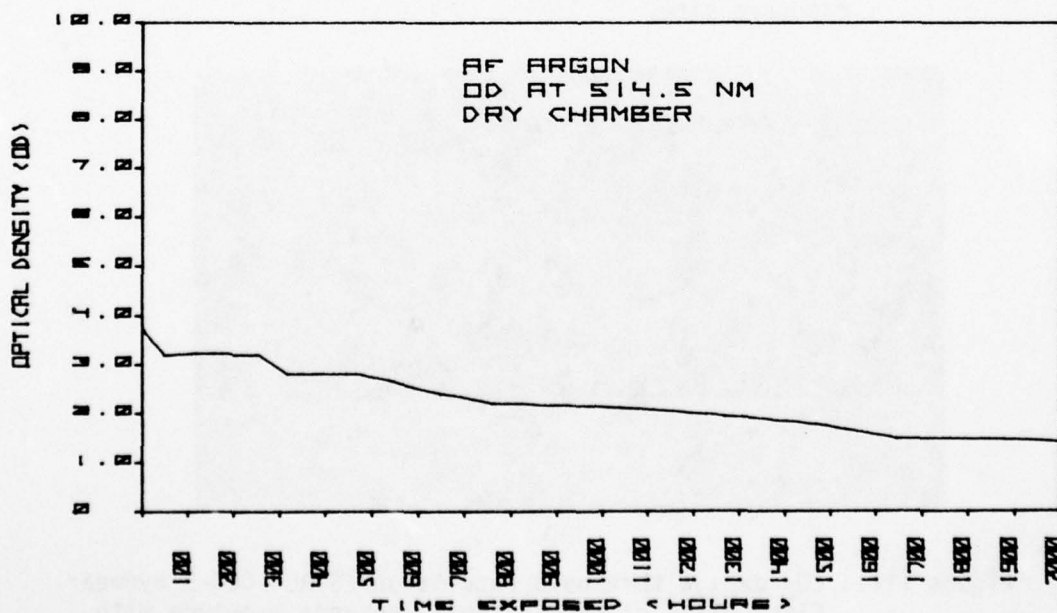


Figure 109. Environmental effects--rate of degradation for AF argon.



Figure 110. CO₂ damage threshold results on AO 680 eyewear. No damage to front plate (glass); however, back plate (plastic) melted and developed cracks at exposure site.

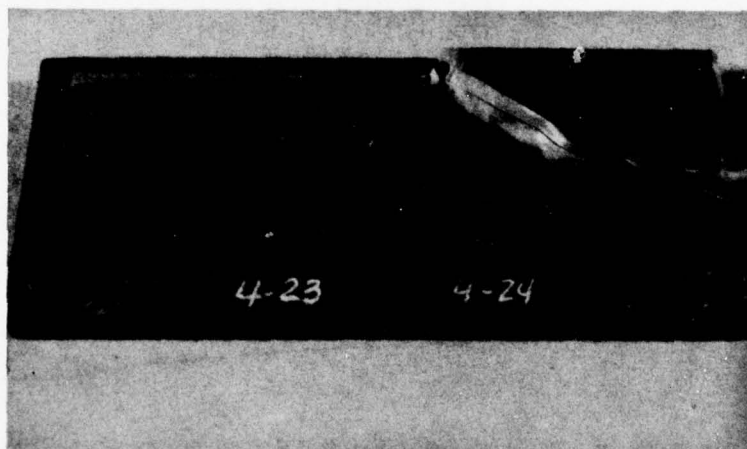


Figure 111. CO₂ damage threshold results on FS AL-1060-9 eyewear. Glass plate cracked after 11 seconds exposure with no prior visible damage.



Figure 112. CO_2 damage threshold results on AF IR-1. Plastic sample melted and bubbled at exposure site.

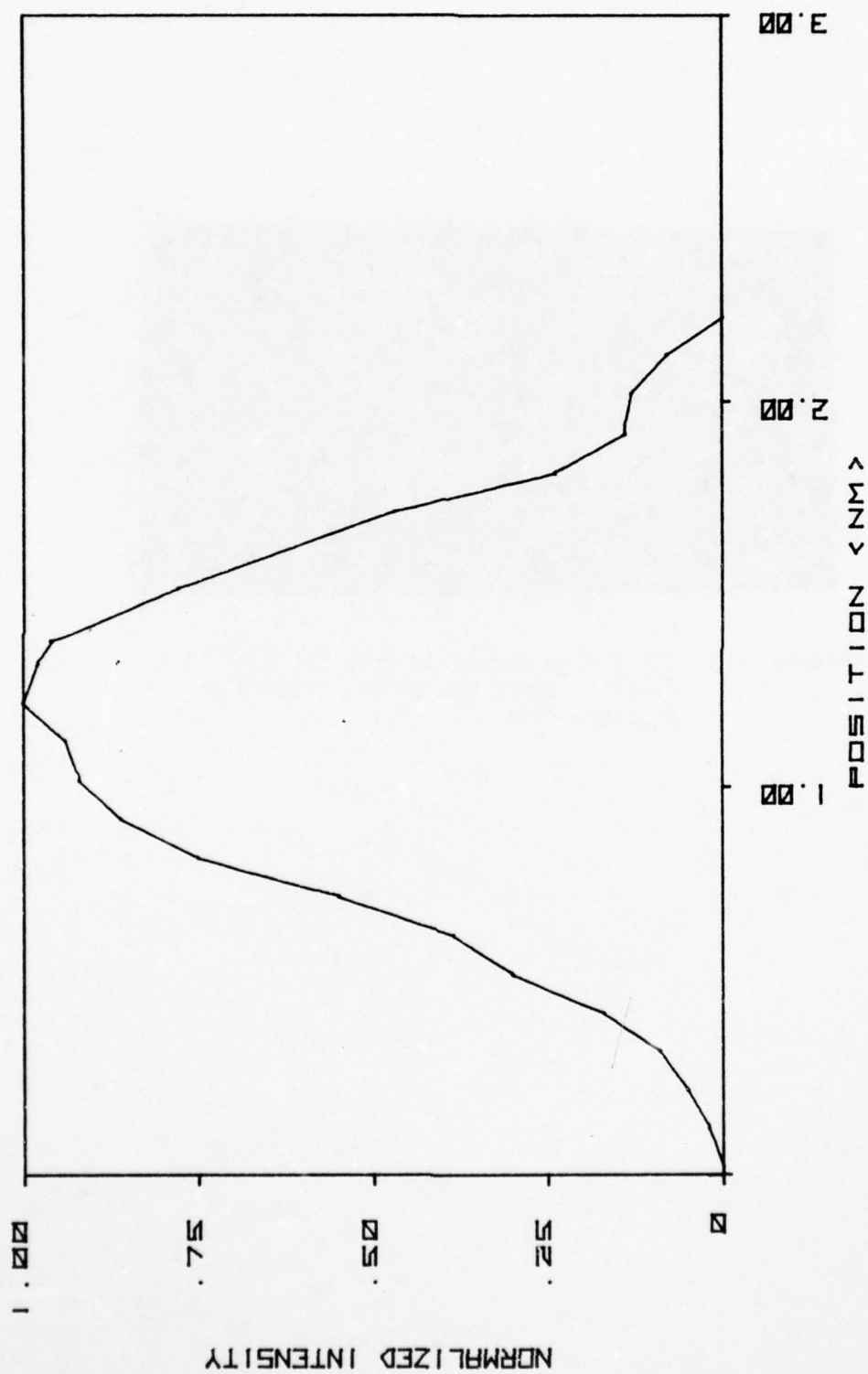


Figure 113. Argon laser beam profile: Normalized intensity vs. position.

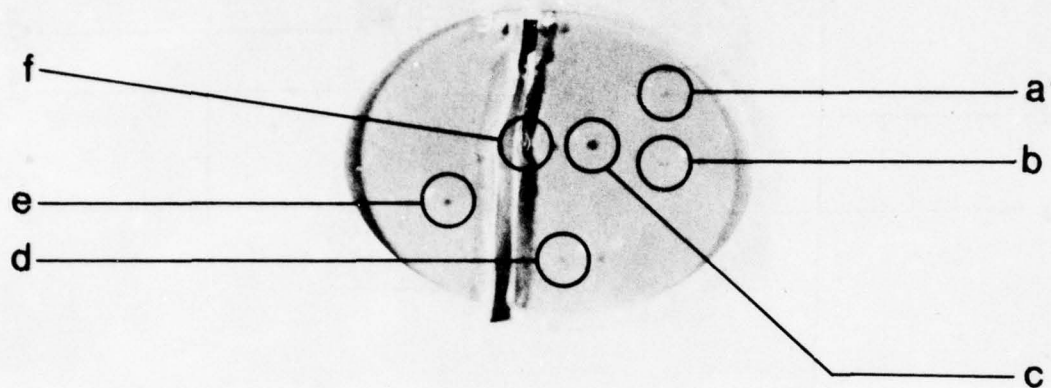


Figure 114. Argon damage threshold results on FS AL-515-7. Exposure sites a, b, c, d, and e are surface blemishes. Exposure site f is a chip at point of exposure resulting in a crack of single-layer glass sample.

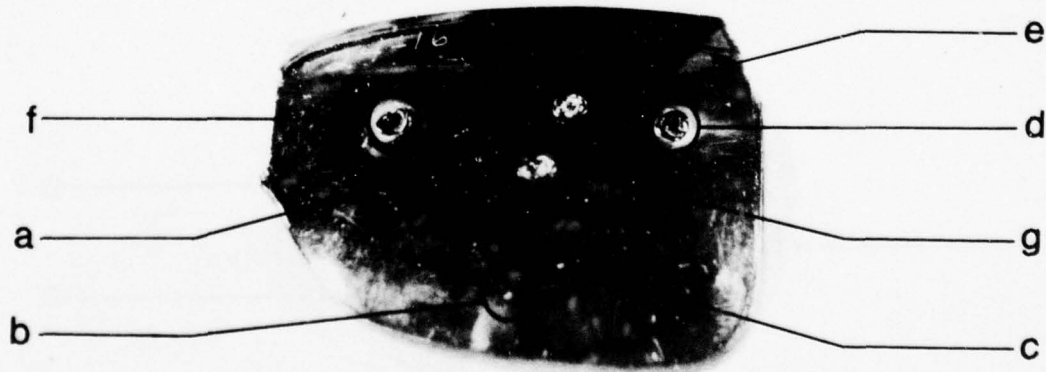


Figure 115. Argon damage threshold results on AF spectacle goggles. Exposure sites a, b, and c are surface blemishes. Sites d, e, and f are complete burn-through while g is partial burn-through of plastic sample.

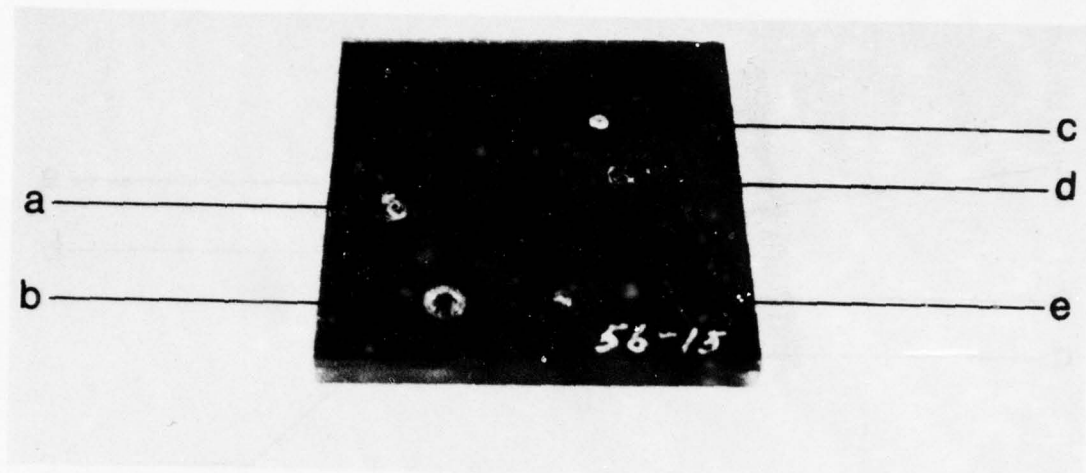


Figure 116. Argon damage threshold results on A0 window laminate. Exposure sites a and b are burned through the first layer and partially burned through the second layer. Exposure sites c, d, and e are bubbles on first layer of multi-layer plastic square.

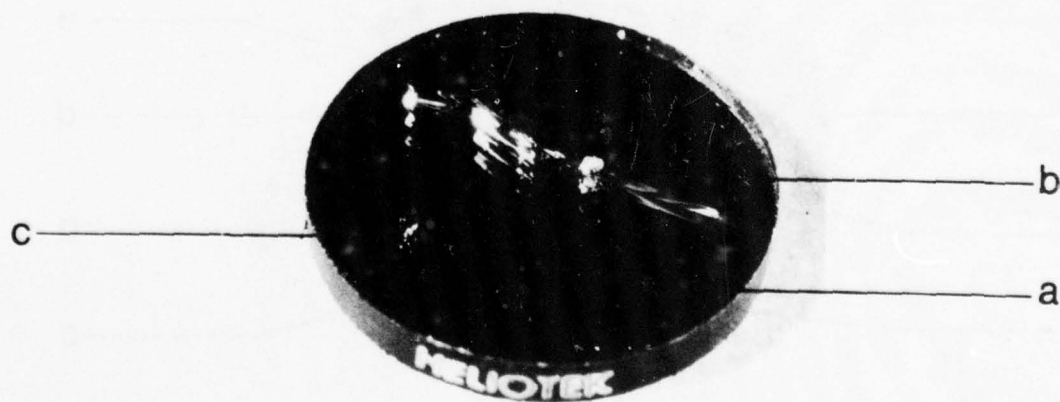


Figure 117. Argon damage threshold results on SL spectrograph. Exposure site a is a surface blemish while b and c are bubble at point of exposure which resulted in cracks in first layer of multi-layer dichroic sample.

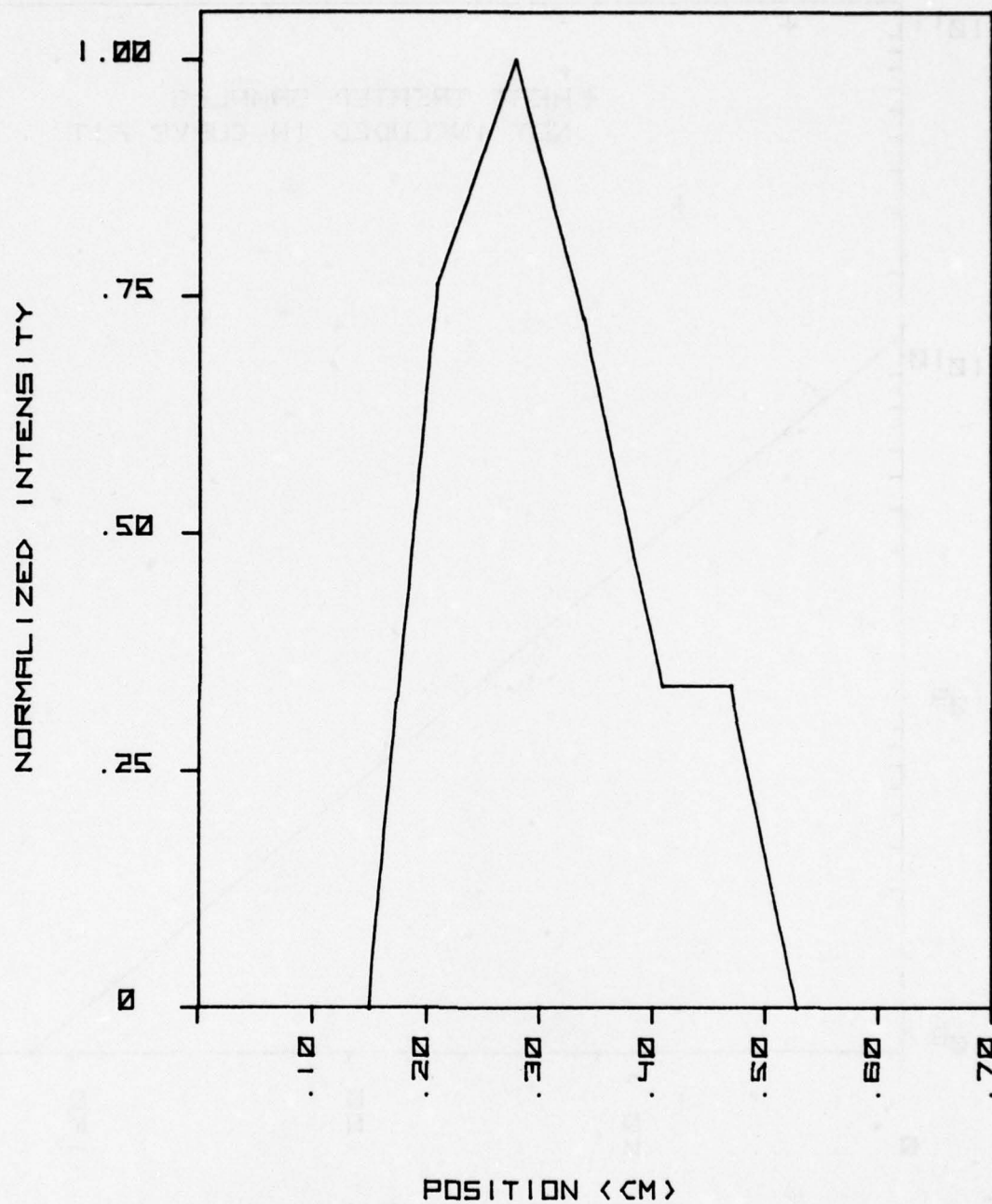


Figure 118. Normalized intensity vs. position of the ruby beam scan for the damage and irreversible transmittance experiments.

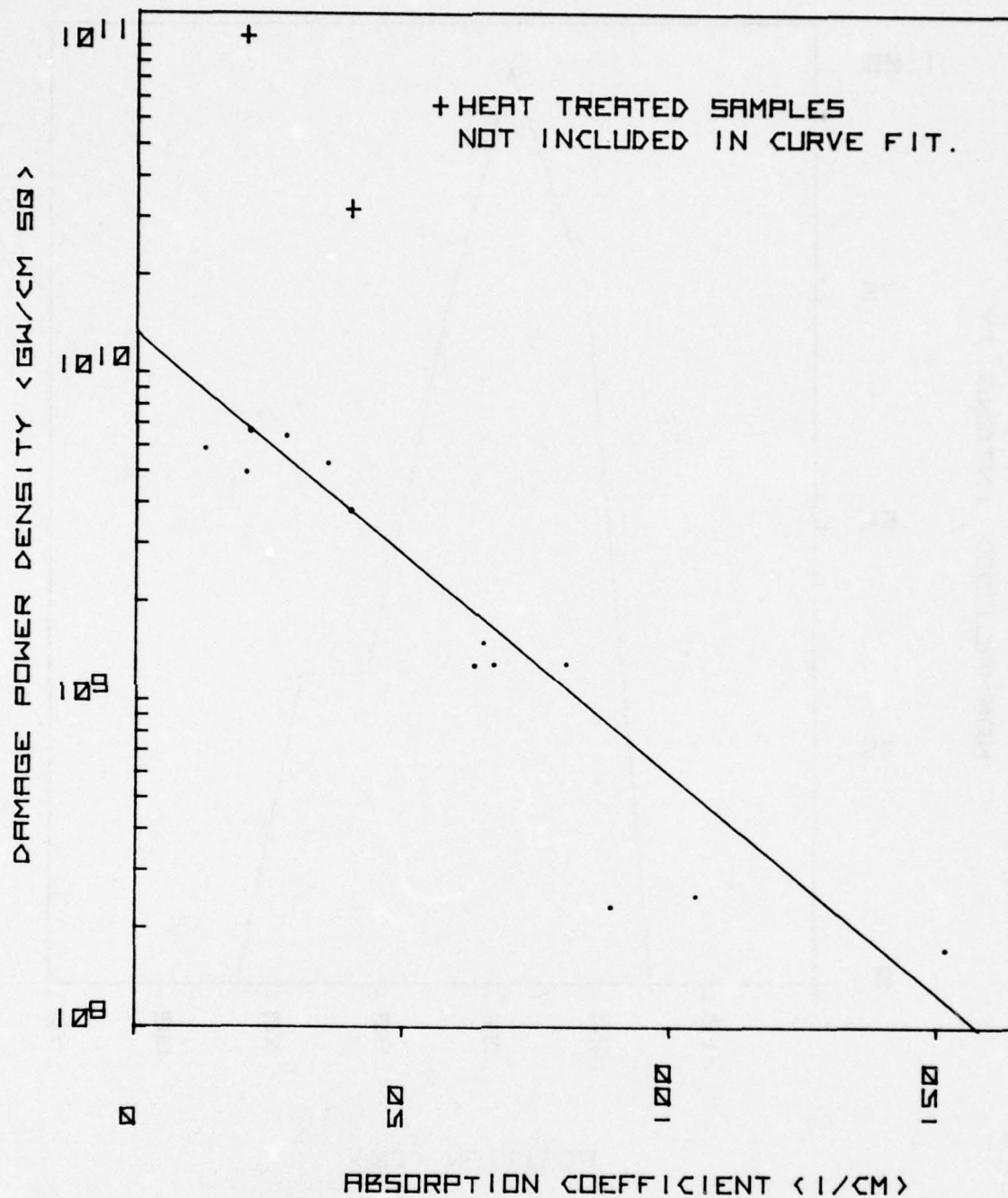


Figure 119. Damage threshold power density vs. absorption coefficient for typical bulk absorbers. The line is from a least-squares linear regression curve fit. The equation for the line in terms of power density, PD, and absorption, α , is the following:

$$PD = 12.2e^{-(0.03\alpha)} (GW/cm^2)$$



Figure 120. Ruby damage threshold results on AF anti-red.
Plastic square discolored at DT.

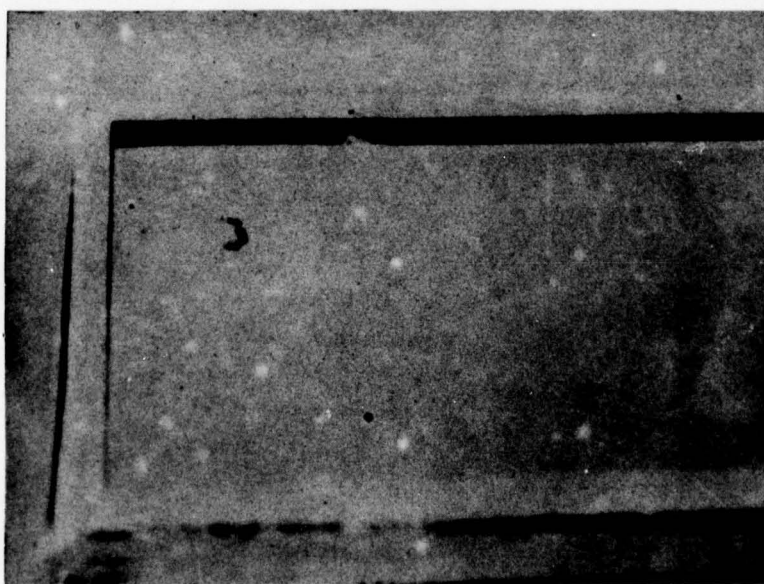


Figure 121. Ruby damage threshold results on BL 5W3756.
Dichroic layer burned away at exposure site.

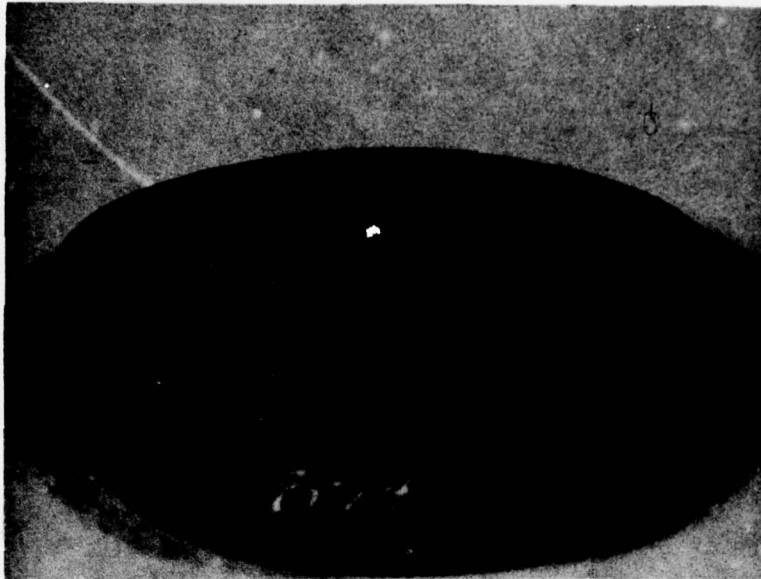


Figure 122. Ruby damage threshold results on A0 588.
Glass lens was pitted at DT.

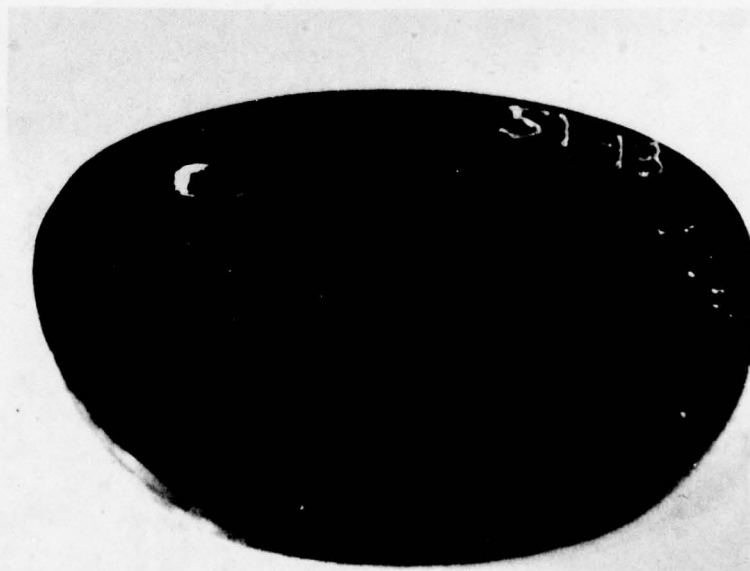
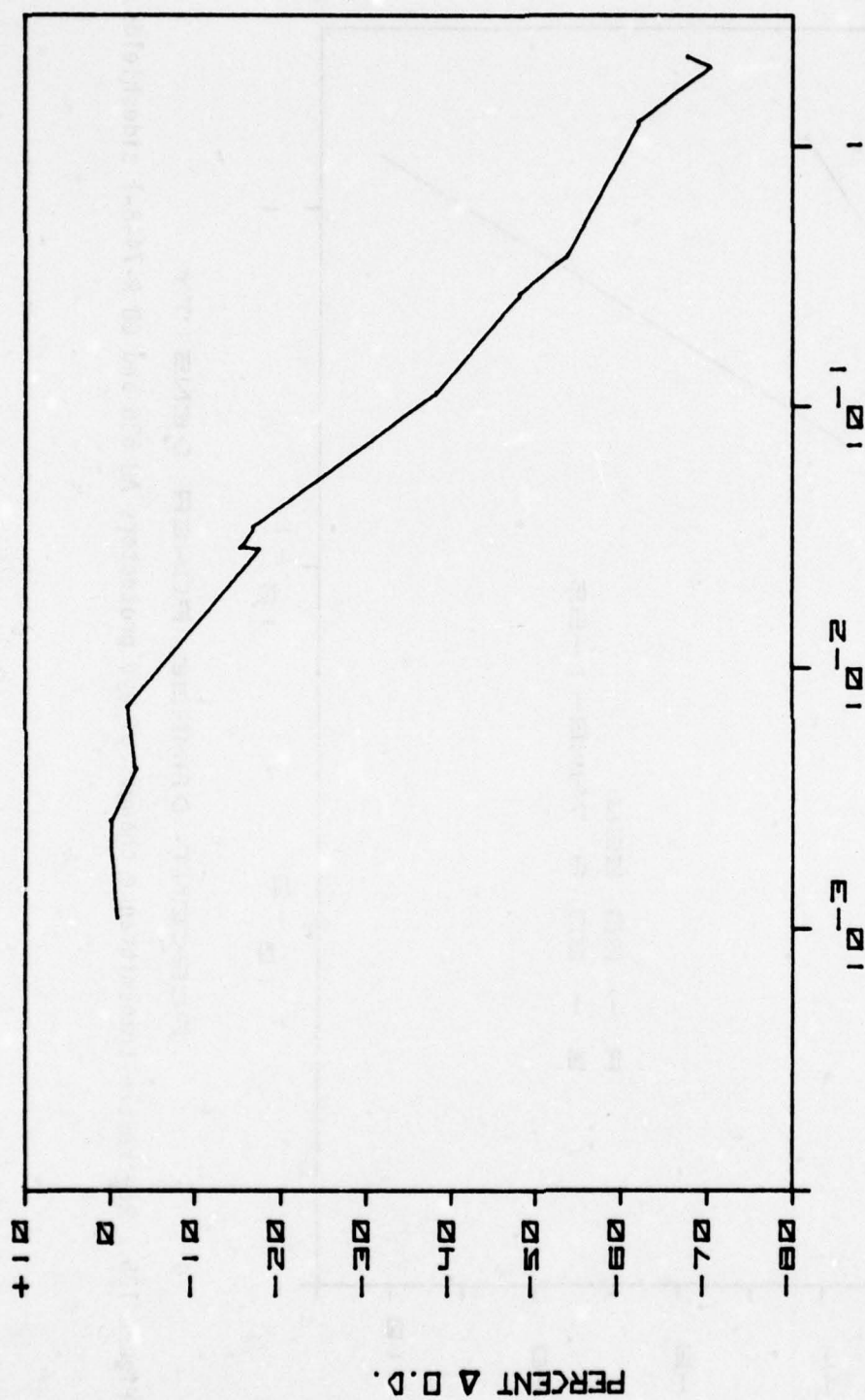
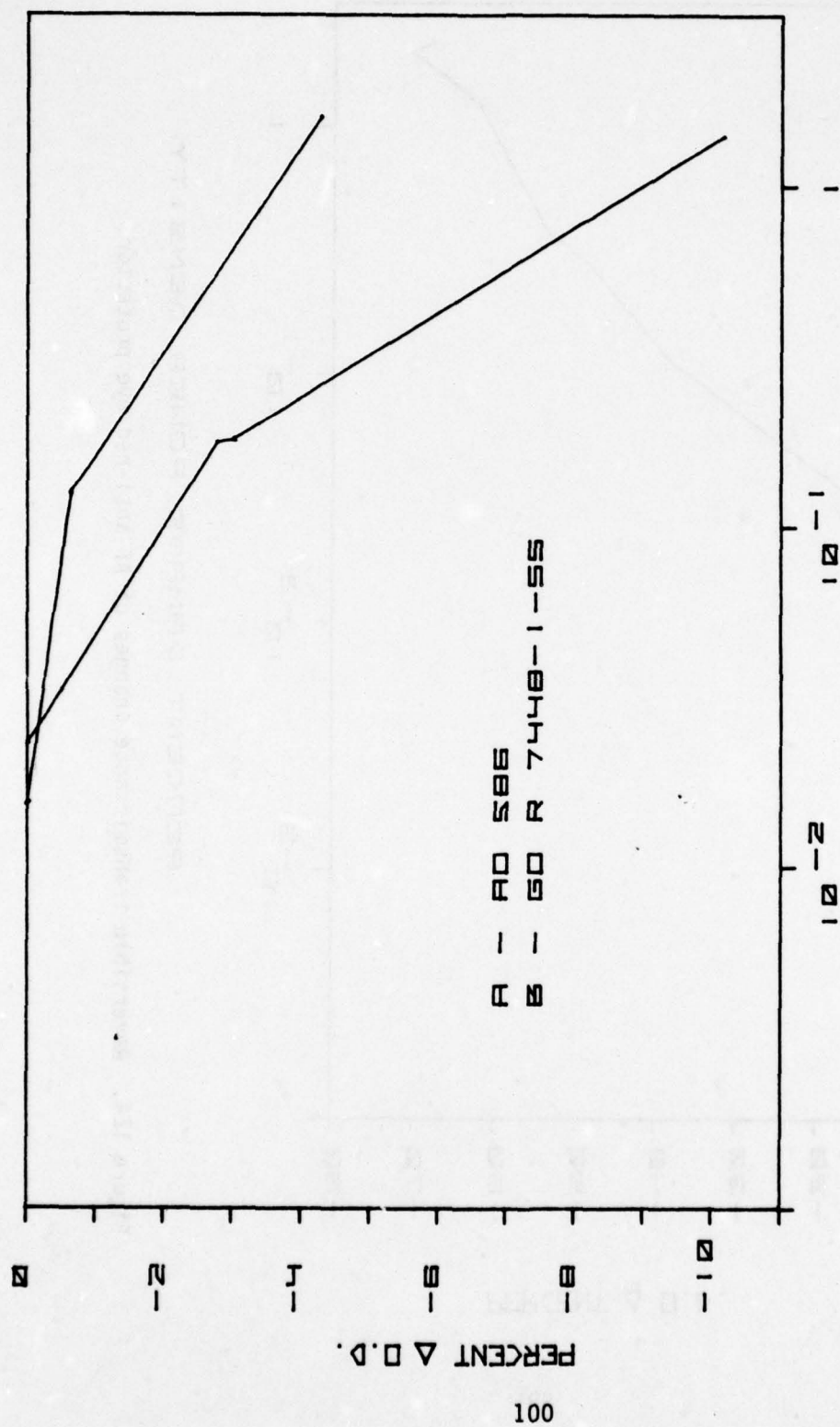


Figure 123. Ruby damage threshold results on G0 LGA.
Plastic lens was pitted at DT.



PERCENT DAMAGE POWER DENSITY

Figure 124. Reversible transmittance changes of AF anti-red eye protector.



PERCENT DAMAGE POWER DENSITY

Figure 125. Reversible transmittance changes of eye protectors A0 586 and G0 R-7448-1 sideshields.

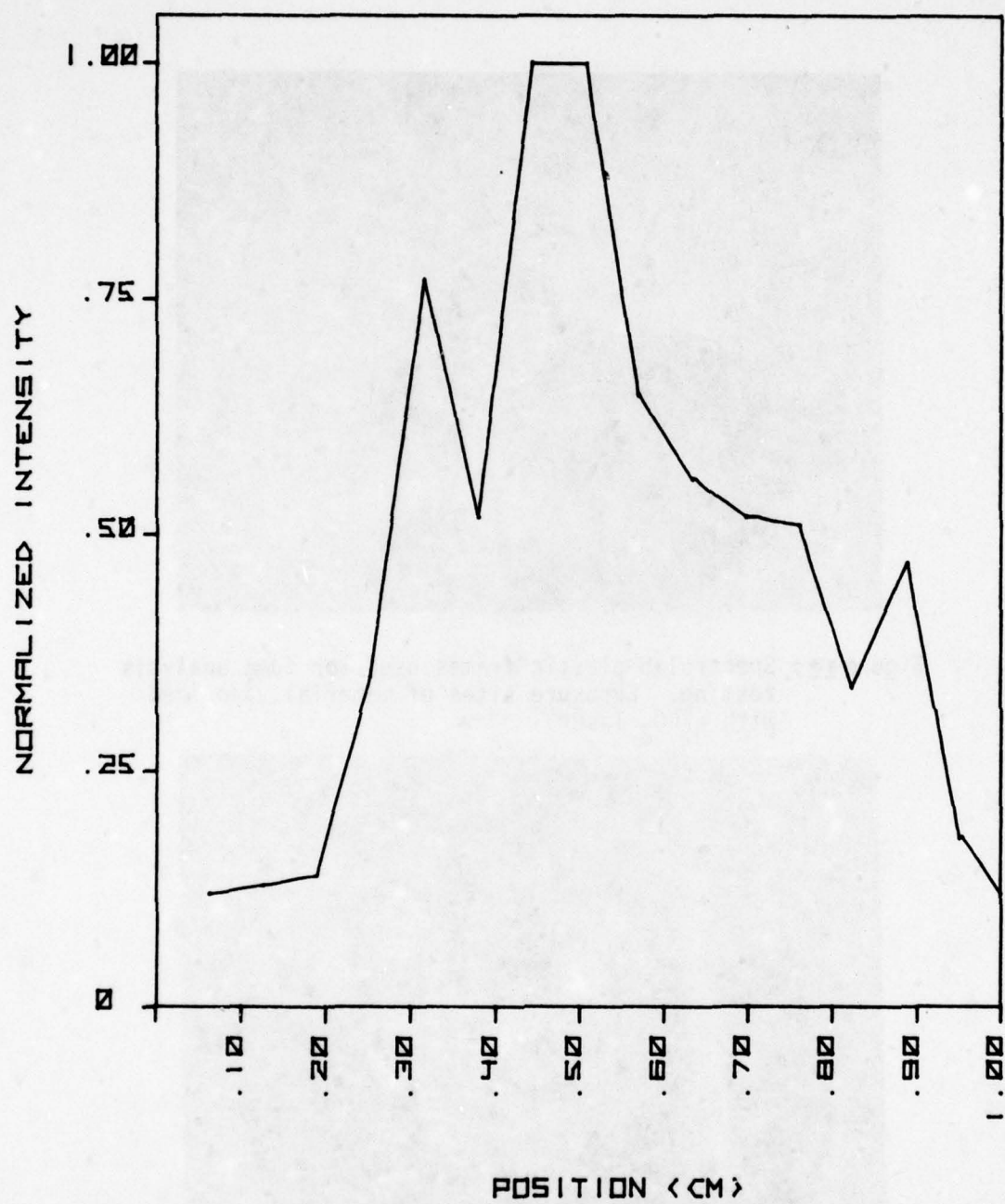


Figure 126. Laser beam intensity profile for reversible transmittance experiment.

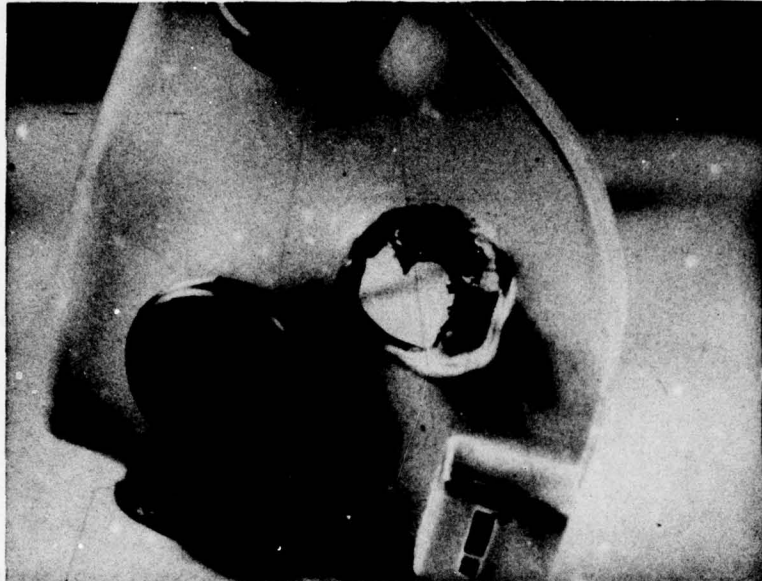


Figure 127. Spectrolab plastic frames used for fume analysis testing. Exposure sites of material vaporized with a CO_2 laser.

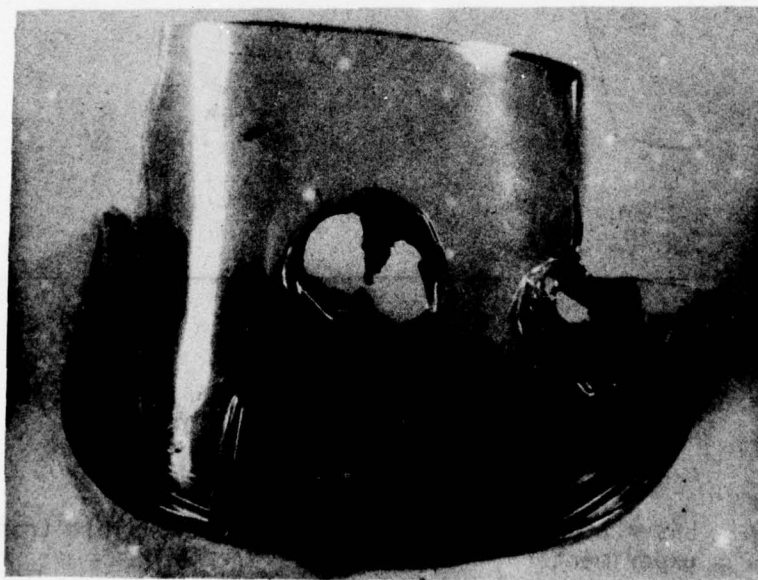


Figure 128. G0 LGS-NN sideshield used for fume analysis testing. Exposure sites of material vaporized with a CO_2 laser.

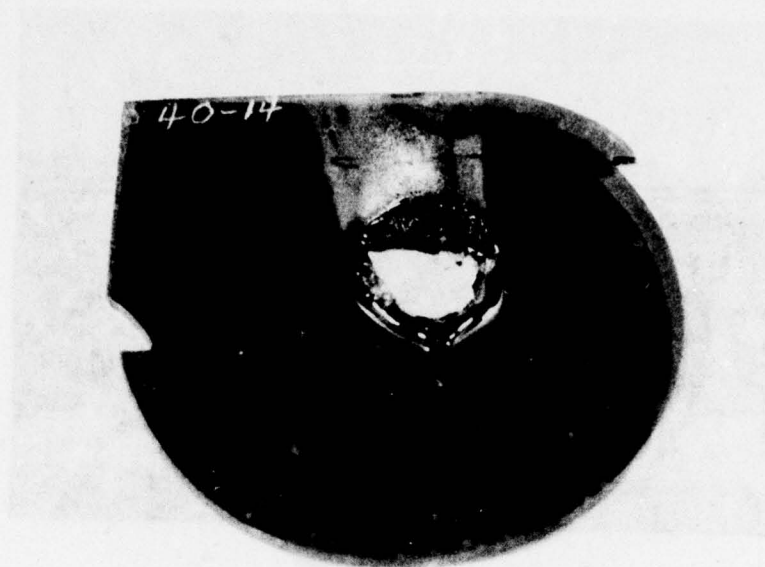


Figure 129. AF IR-1 lens used for fume analysis testing.
Exposure sites of material vaporized with a
CO₂ laser.

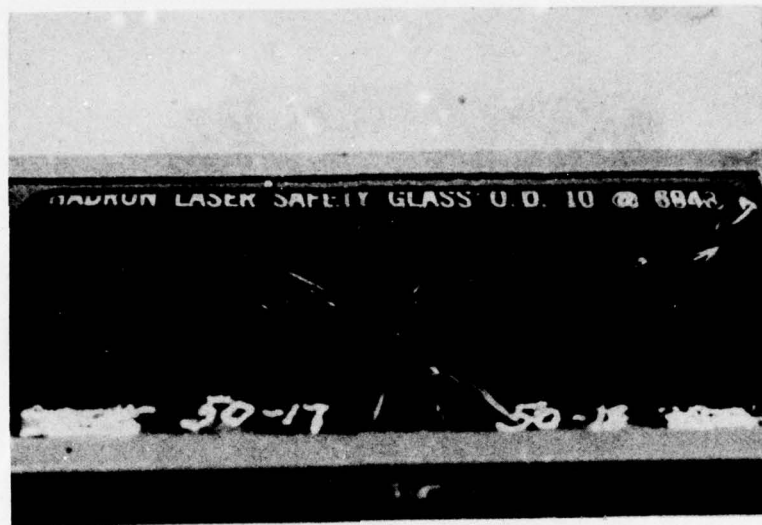


Figure 130. Impact resistance test results on HD 112-1. Front plate (glass) shattered but no damage to back plate (plastic).

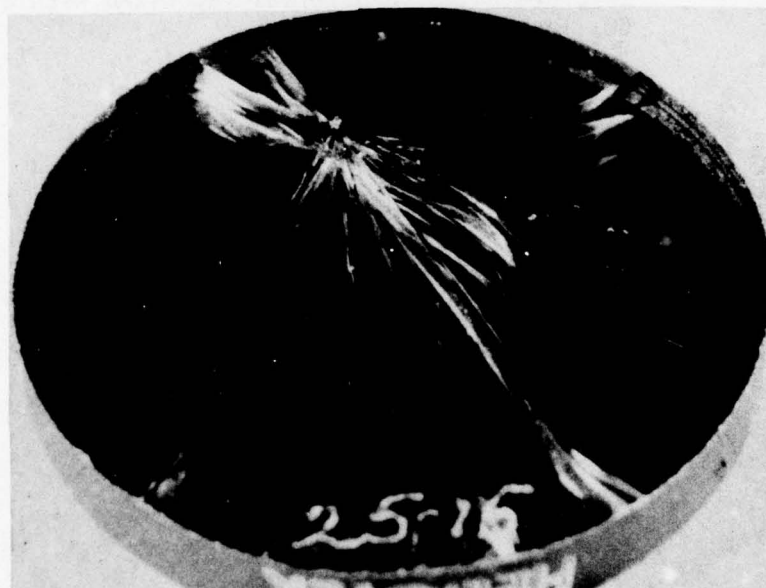


Figure 131. Impact resistance test results on SL Spectrogard. Only front layer shattered (multi-layer glass dichroic lens).

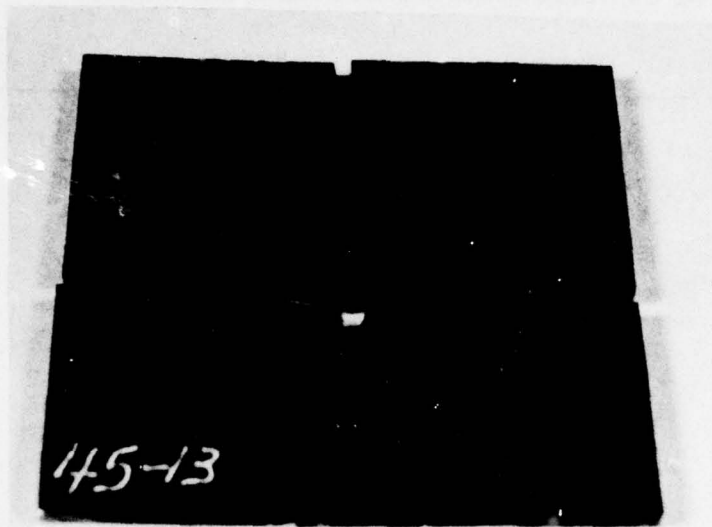


Figure 132. Impact resistance test results on AF IR-2.
Plastic in sheet form.

TABLE 1. LASER-PROTECTION EYEWEAR USED IN STUDY (LENSES)

| Manufacturer | Eyewear type | Material/ configuration ^a | Typical frame configuration (Figure No.) |
|--------------------------|-------------------|---|--|
| American Optical (AO) | 580 | C/Plate | 4 |
| | 581 | C/Plate | 4 |
| | 584 | C/Plate | 4 |
| | 585 | C/Plate | 4 |
| | 586 | G/Spectacle | 2 |
| | 587 | G/Spectacle | 2 |
| | 588 | G/Spectacle | 2 |
| | 598 | G/Spectacle | 2 |
| | 599 | C/Plate | 4 |
| | 680 | C/Plate | 4 |
| | 698 | C/Plate | 4 |
| | Tourgard | P/Spectacle | 2 |
| | Window laminate | P/Sheet form | N/A |
| Bausch & Lomb (BL) | 5W3754 | GIF/Plate | 5 |
| | 5W3755 | GIF/Plate | 5 |
| | 5W3756 | GIF/Plate | 5 |
| | 5W3757 | GIF/Plate | 5 |
| | 5W3758 | GIF/Plate | 5 |
| Fish Schurmann (FS) | AL-515-7 | G/Goggle | 3 |
| | AL-633-5 | G/Plate/Goggle | 3,5 |
| | AL-1060-9 | G/Plate | 5 |
| Glendale Optical (GO) | LGA | P/Spectacle | 2 |
| | LGB | P/Goggle | 6 |
| | LGS-NDGA | P/Goggle | 6 |
| | LGS-A | P/Goggle | 6 |
| | LGS-R | P/Goggle | 6 |
| | LGS-HN | P/Goggle | 6 |
| | LGS-NN | P/Goggle | 6 |
| | A7448-1 | P/Spectacle | 2 |
| | NDGA 7448-1 | P/Spectacle | 2 |
| | HN 7448-1 | P/Spectacle | 2 |
| | R7448-1 | P/Spectacle | 2 |
| | LGU-A | P/Plate | 5 |
| | LGU-R | P/Plate | 5 |
| | LGU-NDGA | P/Plate | 5 |
| | LGU-HN | P/Plate | 5 |
| Hadron (HD) | 112-1 | C/Plate | 4,5 |
| | 112-2 | C/Plate | 4,5 |
| | 112-4 | C/Plate | 4,5 |
| | 112-5 | C/Plate | 4,5 |
| Air Force Issue (AF) | Spectacle Goggle | P/Spectacle | 7 |
| | Visible Spectacle | P/Goggle | 6 |
| | IR-1 | P/Goggle | 6 |
| | Neodymium | P/Sheet | 8 |
| | Anti-Red | P/Sheet | 8 |
| | Argon | P/Sheet | 8 |
| | Multiband | P/Sheet | 8 |
| | IR-2 | P/Goggle | 8 |
| | IR-3 | G/Spectacle | 9 |

TABLE 1. (continued)

| Manufacturer | Eyewear type | Material/ configuration ^a | Typical frame configuration (Figure No.) |
|--|--------------|--------------------------------------|--|
| Spectrolab (SL) (Formerly Heliotek) | Spectrogard | GIF/Goggle | 3 |

^aMaterial symbol used:
 P--Plastic
 G--Glass
 C--Combination
 GIF--Glass interference filter
 R--Rubber/pliable plastic

TABLE 2. LASER-PROTECTION EYEWEAR USED IN STUDY (FRAMES)

| Manufacturer | Eyewear type | Typical material/ configuration ^a (Figure No.) | Dye material in frame |
|-----------------------|----------------------------|---|-----------------------|
| Glendale Optical (GO) | LGS-R | P,6 | Yes |
| | LGS-NDGA | P,6 | Yes |
| | LGS-NN | P,6 | Yes |
| | LGS-HN | P,6 | Yes |
| | A7448-1 | P,2 | Yes |
| | NDGA 7448-1 | P,2 | Yes |
| | HN7448-1 | P,2 | Yes |
| | P7448-1 | P,2 | Yes |
| Spectrolab (SL) | Tan/Opaque | P,3 | No |
| Hadron (HD) | 112 Series Green/Opaque | R,4 | No |

Material symbol used:

P--Plastic
 R--Rubber/pliable plastic

TABLE 3. DIMENSIONAL STANDARD COMPLIANCE--ANSI Z87.1)

| Eyewear | Standard That Applies | | | Meets standard Yes No | |
|----------------|---|---|--|--------------------------|---|
| | Section 6.3.3.1 Lens Thickness 0.118-0.15 in. (0.30-0.38 cm) | Section 6.1.3.5 Plastic goggle Thickness >0.05 in. (0.13 cm) | Section 5.1.4.1.6 Filter plates Thickness 0.08-0.15 in. (0.2-0.38 cm) Length >4.25 in. \pm 0.03 (10.8 cm) Width >2.0 in. \pm 0.03 (5.08 cm) | | |
| AO 580 | | | X | | X |
| 581 | | | X | | X |
| 584 | | | X | | X |
| 585 | | | X | | X |
| 586 | X | | X | | X |
| 587 | X | | | | X |
| 588 | X | | | | X |
| 598 | X | | | X | |
| 680 | | | | X | |
| 698 | | | X | | X |
| Tourgard | X | | X | | X |
| BL 5W3754 | | | | | X |
| 5W3755 | | | X | | X |
| 5W3756 | | | X | | X |
| 5W3757 | | | X | | X |
| 5W3758 | | | X | | X |
| FS AL-515-7 | X | | | | X |
| AL-633-5 | X | | | | X |
| AL-1060-9 | | | X | | X |
| GO LGA | X | | X | | X |
| LGB | | | | | X |
| LGS-NDGA | | X | | X | |
| LGS-A | | X | | X | |
| LGS-R | | X | | X | |
| LGS-HN | | X | | X | |
| LGS-NN | | X | | X | |
| A-7448-1 | X | | | X | |
| NDGA-7448-1 | X | | | | X |
| HN-7448-1 | X | | | | X |
| R-7448-1 | X | | | | X |
| LGU-A | | | | | X |
| LGU-R | | | X | | X |
| LGU-NDGA | | | X | X | |
| LGU-HN | | | X | | X |
| HD 112-1 | | | X | | X |
| 112-2 | | | X | | X |
| 112-4 | | | X | | X |
| 112-5 | | | X | | X |
| SL Spectrogard | X | | | | X |
| AF Spectacle | X | | | | X |
| Goggle | | | | | X |
| Visible | | X | | | |
| Spectacle | | | | X | |
| IR-1 | | X | | | |
| Nd | | X | | X | |
| Anti-Red | | X | | X | |
| Argon | | X | | X | |
| Multiband | | X | | X | |
| IR-2 | | X | | X | |
| IR-3 | X | | | X | |

X

TABLE 4. BASELINE OPTICAL QUALITY MEASUREMENTS

| Manufacturer and type | Rated luminous % transmittance (LT) | Measured LT % Photopic Scotopic | Percent haze filter | | Spherical equivalent (diopters) | Rated optical density (OD) at λ (nm) | Measured OD at λ (nm) |
|------------------------------|--|------------------------------------|------------------------|-----|---------------------------------------|--|----------------------------------|
| | | | A | C | | | |
| <u>American Optical (AO)</u> | | | | | | | |
| A0 580 | 27.6 | 16.7 | 1.8 | 5.0 | 0.0 | 3.4 @ 694.3 | 3.6 @ 694.3 |
| 581 | 10.0 | 3.9 | 0.0 | 0.0 | +0.03 | 4.1 @ 632.8 | 4.4 @ 632.8 |
| 584 | 46.0 | 36.7 | 0.0 | 0.0 | 0.0 | 6.1 @ 694.3 | 5.8 @ 694.3 |
| 585 | 35.0 | 26.1 | 0.0 | 0.4 | 0.0 | 5.0 @ 694.3 | 5.6 @ 694.3 |
| 586 | 27.6 | 14.1 | 0.0 | 0.0 | +0.07 | 13.5 @ 840 | > 4 @ 840 |
| 587 | 10.0 | 1.9 | 0.0 | 0.0 | 0.0 | 10.9 @ 1060 | > 8 @ 1060 |
| 588 | 36.0 | 30.7 | 0.0 | 0.0 | +0.01 | 17.1 @ 1060 | > 8 @ 1060 |
| 598 | 24.0 | 42.9 | 0.3 | 0.7 | +0.01 | 8 @ 694.3 | 7.8 @ 694.3 |
| 599 | 25.0 | 32.7 | 0.4 | 0.3 | 0.0 | 21.0 @ 840 | > 4 @ 840 |
| 680 | 100.0 | 75.1 | 0.6 | 0.6 | 0.0 | 3.4 @ 694.3 | 3.9 @ 694.3 |
| 698 | 5.0 | 5.9 | 0.0 | 0.0 | +0.01 | 4 @ 632.8 | 4.6 @ 632.8 |
| Tourgard | 85.0 | 83.8 | 0.5 | 2.5 | -0.02 | 16 @ 840 | > 4 @ 840 |
| ANSI STD | | | | | | 2.5 @ 632.8 | 2.5 @ 632.8 |
| | | | | | | 7 @ 694.3 | 6.4 @ 694.3 |
| | | | | | | 13.5 @ 1060 | > 8 @ 1060 |
| | | | | | | 9 @ 514.5 | 9.3 @ 458 |
| | | | | | | 14.7 @ 455 | 8.3 @ 514.5 |
| | | | | | | 8 @ 514.5 | 9.3 @ 458 |
| | | | | | | 50 @ 10600 | 8.7 @ 514.5 |
| | | | | | | 8.5 @ 530 | N/A |
| | | | | | | 6.4 @ 1060 | 7.5 @ 530 |
| | | | | | | N/A | 7.4 @ 1060 |
| | | | | | | | N/A |

TABLE 4. (continued)

| Manufacturer and type | Rated luminous % transmittance (LT) | Measured LT % Photopic Scotopic | Percent haze filter | | Spherical equivalent (diopters) | Rated optical density (OD) at λ (nm) | Measured OD at λ (nm) |
|-----------------------|-------------------------------------|---------------------------------|---------------------|-----|---------------------------------|--|-------------------------------|
| | | | A | C | | | |
| AO Window Laminate | | | | | | | |
| | 25.0 | 23.8 57.6 | 0.0 | 0.0 | +0.0 | 6 @ 365 | 5.5 @ 365 |
| | | | | | | 6 @ 488 | >10.0 @ 488 |
| | | | | | | 6 @ 514.5 | 9.9 @ 514.5 |
| | | | | | | 4 @ 530 | 4.4 @ 530 |
| | | | | | | 1.2 @ 633 | 1.2 @ 633 |
| | | | | | | 2.3 @ 671 | 3.0 @ 671 |
| Bausch and Lomb (BL) | | | | | | | |
| BL 5W3754 | Mfgr. states significant amount | 6.4 0.0 | 0.0 | 0.0 | 0.0 | 25 @ 365 | >7.0 @ 365 |
| | | | | | | 17 @ 458 | 9.9 @ 458 |
| | | | | | | 16 @ 488 | >10.0 @ 488 |
| | | | | | | 14 @ 514.5 | >10.0 @ 514.5 |
| | | | | | | 11 @ 530 | 9.9 @ 530 |
| 5W3755 | " | 58.2 22.1 | 2.9 | 3.2 | 0.0 | 7 @ 458 | 7.8 @ 458 |
| 5W3756 | " | 8.5 22.3 | 0.0 | 1.0 | 0.0 | 15 @ 694.3 | >10.0 @ 694.3 |
| 5W3757 | " | 1.7 4.5 | 0.0 | 0.0 | 0.0 | 7.5 @ 694.3 | 7.3 @ 694.3 |
| 5W3758 | " | 2.2 1.5 | 0.0 | 0.0 | 0.0 | 6.5 @ 1060 | 7.3 @ 1060 |
| Fish Schurman (FS) | | | | | | | |
| FS AL-515-7 | Mfgr. quotes high visibility | 55.2 10.1 | 3.6 | 4.1 | 0.0 | 10.0 @ 488 | >10.0 @ 488 |
| AL-633-5 | " | 21.1 37.7 | 0.0 | 0.0 | 0.0 | 7 @ 514.5 | >10.0 @ 514.5 |
| | | | | | | 30+ @ 1060 | >8 @ 1060 |
| | | | | | | 5 @ 632.8 | 3.8 @ 632.8 |
| | | | | | | 10.0 @ 694.3 | >10.0 @ 694.3 |

TABLE 4. (continued)

| Manufacturer and type | Rated luminous % transmittance (LT) | Mfg. quotes high visibility | Measured LT % | | Percent haze | | Spherical equivalent (diopters) | Rated optical density (OD) at λ (nm) | Measured OD at λ (nm) |
|------------------------------|-------------------------------------|-----------------------------|---------------|----------|--------------|-----|---------------------------------|--|---|
| | | | Photopic | Scotopic | A | C | | | |
| FS AL-1060-9 | | | 65.5 | 67.1 | 0.0 | 0.0 | | 5 @ 900 9 @ 1060-1400 6 @ 1800 5+ @ 3400 | >4 @ 900 >4 @ 1060-1400 >4 @ 1800 >4 @ 3400 >8 @ 1060 |
| <u>Glendale Optical (GO)</u> | | | | | | | | | |
| LGA | 20.0 | | 0.4 | 0.4 | 0.0 | 0.0 | -0.20 | 30 @ 1060 20 @ 365 6 @ 694.3 14 @ 365 11 @ 488 7 @ 514.5 4 @ 530 4 @ 1060 15 @ 488 11 @ 514.5 6 @ 694.3 6 @ 632.8 15 @ 332 16 @ 337 14 @ 840 14 @ 1060 15 @ 488 11 @ 514.5 6 @ 632.8 | >8 @ 1060 >7.0 @ 365 >10.0 @ 694.3 >7.0 @ 365 >10.0 @ 488 7.6 @ 514.5 4.0 @ 530 4.3 @ 1060 10.0 @ 488 10.0 @ 514.5 7.3 @ 694.3 5.3 @ 632.8 >4 @ 332 >4 @ 337 >4 @ 840 >8 @ 1060 >10.0 @ 488 8.7 @ 514.5 5.3 @ 632.8 |
| LGB | 45.0 | | 4.6 | 6.2 | 0.1 | 0.5 | -0.02 | | |
| LGS-A | 45.0 | | 41.5 | 5.7 | 4.8 | 5.2 | -0.02 | | |
| LGS-R | 20.0 | | 17.4 | 35.7 | 0.1 | 2.2 | -0.02 | | |
| LGS-HN | 20.0 | | 26.0 | 59.4 | 0.0 | 1.3 | -0.01 | | |
| LGS-NN | 70.0 | | 82.4 | 65.2 | 1.0 | 1.0 | 0.0 | | |
| LGS-NDGA | 45.0 | | 4.6 | 6.2 | 0.1 | 0.5 | -0.03 | | |
| A7448-1 | 45.0 | | 46.3 | 6.4 | 1.8 | 2.3 | -0.21 | | |
| HN7448-1 | 20.0 | | 21.6 | 58.8 | 0.0 | 1.4 | -0.18 | | |

TABLE 4. (continued)

| Manufacturer and type | Rated luminous % transmittance (LT) | Measured LT % Photopic Scotopic | Percent haze | | Spherical equivalent (diopters) | Rated optical density (OD) at λ (nm) | Measured OD at λ (nm) |
|--------------------------|--|------------------------------------|--------------|-----|---------------------------------------|---|---|
| | | | A | C | | | |
| GO NDGA-7448-1 | 45.0 | 7.5 4.4 | 0.0 | 0.0 | -0.22 | 14 @ 840 14 @ 1060 | >4 @ 840 >8 @ 1060 |
| R 7448-1 | 20.0 | 14.2 30.8 | 0.0 | 1.3 | -0.16 | 6 @ 694.3 | 7.5 @ 694.3 |
| LGU-A | 45.0 | 47.7 8.5 | 3.4 | 3.4 | 0.05 | 15 @ 488 | >10.0 @ 488 |
| LGU-HN | 20.0 | 23.8 57.6 | 0.0 | 1.3 | -0.07 | 11 @ 514.5 | >10.0 @ 514.5 |
| LGS-NDGA | 45.0 | 25.4 5.1 | 0.0 | 0.0 | -0.07 | 6 @ 632.8 14 @ 1060 | 5.4 @ 632.8 >8 @ 1060 |
| LGU-R | 20.0 | 21.6 42.4 | 0.0 | 0.8 | -0.07 | 14 @ 840 6 @ 694.3 | >4 @ 840 7.1 @ 694.3 |
| <u>Hadron (HD)</u> | | | | | | | |
| HD 112-1 | No statement | 22.4 36.5 | 0.0 | 0.0 | +0.01 | 10 @ 694.3 | 10.0 @ 694.3 |
| 112-2 | " | 18.7 0.9 | 0.0 | 0.0 | 0.0 | 10 @ 530 | >10.0 @ 530 |
| 112-4 | " | 68.4 68.6 | 0.7 | 0.7 | +0.01 | 10 @ 10600 | N/A |
| 112-5 | " | 0.4 0.0 | 0.0 | 0.0 | 0.0 | 10 @ 514.5 | >10.0 @ 514.5 |
| <u>Spectrolab (SL)</u> | | | | | | | |
| SL Spectrogard | Mfgr. specifies high visibility | 12.9 4.6 | 0.0 | 0.0 | 0.0 | 5 @ 514.5 7 @ 632.8 9 @ 694.3 | 7.7 @ 514.5 6.1 @ 632.8 >10.0 @ 694.3 |
| <u>Air Force (AF)</u> | | | | | | | |
| AF Spectacle Goggle | 25.0 | 11.4 2.7 | 1.4 | 2.5 | -0.15 | 6 @ 365 6 @ 488 4 @ 530 1.2 @ 633 2.3 @ 671 | >7.0 @ 365 >10.0 @ 488 6.5 @ 514.5 4.3 @ 530 1.5 @ 633 3 @ 671 |

TABLE 4. (continued)

| Manufacturer and type | Rated luminous % transmittance (LT) | Measured LT % | | Percent haze | | Spherical equivalent (diopters) | Rated optical density (OD) at λ (nm) | Measured OD at λ (nm) |
|--------------------------|--|---------------|----------|--------------|-----|---------------------------------------|--|----------------------------------|
| | | Photopic | Scotopic | A | C | | | |
| AF Visible | ANSI STD | | | | | | | |
| Spectacle | 85.0 | 86.9 | 86.3 | 3.5 | 3.7 | 0.0 | N/A | N/A |
| AF Neodymium | 69.0 | 68.8 | 58.3 | 0.5 | 0.5 | +0.01 | 4.1 @ 1060 | 4.3 @ 1060 |
| AF Anti-Red | 47.0 | 48.9 | 73.5 | 0.0 | 0.0 | 0.0 | 18 @ 632.8 | 2.3 @ 632.8 |
| AF Argon | 72.0 | 59.8 | 14.1 | 0.0 | 0.1 | 0.0 | 5.5 @ 694.3 | 6.4 @ 694.3 |
| AF Multiband | 52.0 | 35.0 | 6.6 | 0.1 | 0.1 | 0.0 | 5 @ 488 | 5.1 @ 488 |
| | | | | | | | 5 @ 514.5 | 3.8 @ 514.5 |
| | | | | | | | 6 @ 365 | >7 @ 365 |
| | | | | | | | 6 @ 488 | >10.0 @ 488 |
| | | | | | | | 6 @ 514.5 | >10.0 @ 514.5 |
| | | | | | | | 4.1 @ 530 | 6.3 @ 530 |
| | | | | | | | 5 @ 300-400 | >7 @ 365 |
| AF IR-1 | 35.0 | 68.8 | 58.3 | 0.5 | 0.5 | +0.01 | 3+ @ 780-1760 | @ 780-1760 |
| | | | | | | | 4 @ 1060 | 4.3 @ 1060 |
| | | | | | | | 3 @ 2.755- | 3 @ 2.755- |
| | | | | | | | 14.0 μ m | 14.0 μ m |
| AF IR-2 | 35.0 | 66.0 | 40.0 | 0.0 | 0.0 | 0.0 | Same as IR-1 | Same as IR-1 |
| AF IR-3 | 60.0 | 61.8 | 66.7 | 0.0 | 0.0 | +0.11 | 4 @ 1060 | 4.3 @ 1060 |

TABLE 5. COMPLIANCE WITH REFRACTIVE AND PRISMATIC STANDARDS--ANSI Z87.1

| Eyewear | Standard That Applies | | Meets standard | |
|-----------------|---|--|----------------|----|
| | Section 5.1.4.1.6(2) Plate Prismatic effect 1/8 prism ° Diopters (Δ) | Section 6.3.2.2 Lens Refractive effect 1/16 Diopters Prismatic effect 1/8 | Yes | No |
| AO 580 | X | | X | |
| 581 | X | | X | |
| 584 | X | | X | |
| 585 | X | | X | |
| 586 | | | | |
| 587 | | X | | X |
| 588 | | X | X | |
| 598 | | X | X | |
| 599 | X | | X | |
| 680 | X | | X | |
| 698 | X | | X | |
| Tourgard | | | X | |
| Window Laminate | X | X | X | |
| BL 5W3754 | X | | X | |
| 5W3755 | X | | X | |
| 5W3756 | X | | X | |
| 5W3757 | X | | X | |
| 5W3758 | X | | X | |
| FS AL-515-7 | | X | X | |
| AL-633-5 | X | X | X | |
| AL-1060-9 | X | | X | |
| GO LGA | | X | | X |
| LGB | | X | X | |
| LGS-NDGA | | X | X | |
| LGS-A | | X | X | |
| LGS-R | | X | X | |
| LGS-HN | | X | X | |
| LGS-NN | | X | X | |
| A-7448-1 | | X | | X |
| NDGA-7448-1 | | X | | X |
| HN-7448-1 | | X | | X |
| R-7448-1 | | X | | X |
| LGU-A | X | | | X |
| LGU-R | X | | | X |
| LGU-NDGA | X | | | X |
| LGU-HN | X | | | X |
| HD 112-1 | X | | X | |
| 112-2 | X | | X | |
| 112-4 | X | | X | |
| 112-5 | X | | X | |
| SL Spectrogard | | X | | X |
| AF Spectacle | | X | | X |
| Goggle | | | | |
| Visible | | X | X | |
| Spectacle | | | | |
| IR-1 | | X | X | |
| IR-2 | X | | X | |
| IR-3 | | X | | X |
| Neodymium | X | | X | |
| Anti-Red | X | | X | |
| Argon | X | | X | |
| Multiband | X | | X | |

TABLE 6. QUALITATIVE SHADING ASSESSMENT--ANSI Z87.1

| Eyewear | Section 5.2.8.3 Shade C-Clear L-Light M-Medium D-Dark | Meets shade standard | | | |
|----------------|--|---|----|----------|----|
| | | C-85% L-50% +7 M-23% +6 D-14% +6 | | | |
| | | Photopic | | Scotopic | |
| | | Yes | No | Yes | No |
| AO 580 | M | X | | X | |
| 581 | D | | X | X | |
| 584 | M | X | | X | |
| 585 | M | X | | X | |
| 586 | M | | X | X | |
| 587 | D | | X | X | |
| 588 | M | X | | X | |
| 598 | M | X | | | X |
| 599 | M | X | | | X |
| 680 | C | | X | | X |
| 698 | D | | X | | X |
| Tourgard | C | X | | X | |
| Window | D | X | | X | |
| Laminate | | | | | |
| BL 5W3754 | D | | X | | X |
| 5W3755 | M | X | | X | |
| 5W3756 | D | X | | X | |
| 5W3757 | D | | X | | X |
| 5W3758 | D | | X | | X |
| FS AL-515-7 | M | X | | | X |
| AL-633-5 | M | X | | X | |
| AL-1060-9 | L | X | | X | |
| GO LGA | D | | X | | X |
| LGB | M | X | | | X |
| LGS-A | M | X | | | X |
| LGS-R | M | X | | X | |
| LGS-HN | M | X | | X | |
| LGS-NN | L | X | | X | |
| LGS-NDGA | D | | X | | X |
| A-7448-1 | M | X | | | X |
| HN-7448-1 | M | X | | X | |
| NDGA-7448-1 | D | X | | | X |
| R-7448-1 | D | X | | X | |
| LGU-A | M | X | | | X |
| LGU-HN | M | X | | X | |
| LGU-NDGA | D | X | | | X |
| LGU-R | M | X | | X | |
| HD 112-1 | M | X | | X | |
| 112-2 | D | X | | | X |
| 112-4 | C | | X | | X |
| 112-5 | D | | X | | X |
| SL Spectrogard | M | | X | | X |
| AF IR-1 | M | X | | X | |
| IR-2 | M | X | | X | |
| IR-3 | L | X | | X | |
| Visible | C | X | | X | |
| Spectacle | | | | | |
| Anti-Red | M | X | | X | |
| Argon | M | X | | X | |
| Multiband | M | X | | | X |
| Neodymium | L | X | | X | |
| Spectacle | | | | | |
| Goggle | M | | X | | X |

TABLE 7. QUALITATIVE ASSESSMENT OF SAMPLES EXPOSED IN ENVIRONMENTAL CHAMBERS

| Sample | 2000 hr. exposure at ≤20% humidity 125°F | 2000 hr. exposure at ≥75% humidity 125°F |
|------------------------|--|---|
| AO 580 | No change | Moisture seeped into air gap, surface deterioration on in- side of plates. |
| 581 | No change | Clear plastic plate on some samples deteriorated. |
| 584 | No change | Moisture seeped into air gap, surface speckling on inside of plates. |
| 585 | No change | Moisture seeped into air gap, surface deterioration on in- side of plates. |
| 586 | No change | No change |
| 588 | No change | No change |
| 598 | No change | No change |
| 599 | No change | Moisture seeped into air gap, some surface deterioration on inside of plates. |
| 680 | No change | Surface speckling |
| 698 | No change | Moisture seeped into air gap, speckled effect on inside of plates. |
| Tourgard | No change | Yellowed |
| Window laminate | Darkened | Darkened |
| BL 5W3754 | No change | Moisture seeped into air gap, some speckling on inside of plates. |
| 5W3755 | Surface speckling, striae | Moisture seeped into air gap, surface speckling on inside of plates. |
| 5W3756 | Dichroic coating appeared to be faded. | Moisture seeped into air gap, dichroic coating cracked, worn away at edges. |
| 5W3757 | No change | No change |
| 5W3758 | No change | Moisture seeped into air gap, dichroic film deteriorated at edges, cracked. |
| FS AL-515-7 | No change | No change |
| AL-633-5 | No change | No change |
| AL-1060-9 | No change | No change |
| GO LGA | Faded, striae | Darkened, striae, severe surface deterioration |
| LGB | Faded | Faded |
| LGS-A | Faded, almost bleached | Faded |
| LGS-NDGA | Faded, striae | Faded, striae, surface deterioration |
| LGS-NDGA sideshield | Darkened | Darkened, unevenly |
| LGS-NN | Faded | Bleached |
| LGS-NN sideshield | Bleached | Bleached |

TABLE 7. (continued)

| Sample | 2000 hr. exposure at ≤20% humidity 125°F | 2000 hr. exposure at ≥75% humidity 125°F |
|---------------------------|---|--|
| LGS-HN | Faded slightly | Faded |
| LGS-HN sideshield | Uneven fading, bleaching in spots. | Uneven fading, bleaching in spots. |
| LGS-R | Faded, striae | Faded, striae |
| LGS-R sideshield | Two samples darkened. The rest faded in splotches and turned green. | Two samples darkened in splotches. The rest faded unevenly and turned green. |
| A-7448-1 | Faded, striae | Faded, striae, surface deterioration |
| A-7448-1 sideshield | Bleached, brittle | Bleached, brittle |
| HN-7448-1 | Faded | Bleached |
| HN-7448-1 sideshield | Samples splotched prior to exposure, bleached in splotches. | Samples splotched prior to exposure, bleached in splotches. |
| NDGA-7448-1 | Faded | Faded, striae |
| NDGA-7448-1 sideshield | Faded, brittle | Changed color from green to yellowish-green, brittle. |
| R-7448-1 | Faded, striae | Faded, striae |
| R-7448-1 sideshield | Faded slightly | Faded slightly |
| LGU-A | Faded, almost bleached, striae | Faded, striae |
| LGU-HN | Faded | Bleached |
| LGU-NDGA | Faded, surface speckling | Faded, striae |
| LGU-R | Faded, striae | Faded, striae |
| HD 112-1 | No change | Moisture seeped into air gap, surface deterioration on side of plates. |
| 112-2 | No change | No change |
| 112-4 | No change | No change |
| 112-5 | No change | No change |
| SL Spectrogard | (1) Sample had moisture seep in between plates, rings, rest--no change. | (1) Sample had moisture seep in between plates, rings formed, rest--no change. |
| AF Spectacle Goggle | Faded, striae, severe surface deterioration | Faded, striae, crinkle effect on surface. |
| Visible spectacle | Yellowed, striae | Yellowed |
| Anti-Red | Faded | Faded |
| Argon | Faded | Faded |
| Neodymium | Faded | Bleached |
| Multiband | Faded | Faded |
| IR-1 | Faded | Faded |
| IR-2 | Faded | Faded |
| IR-3 | No change | No change |

TABLE 8. CO₂ DAMAGE THRESHOLD (VISIBLE) RESULTS

| Sample | Avg. laser power (W) | At sample total energy (J) | Exposure time (sec) | Comments |
|-------------------------|----------------------------|----------------------------------|------------------------|--|
| AO 680 | 15.8 | 284.0 | 18.0 | No damage |
| | 26.0 | 390.0 | 15.0 | Damage |
| | 26.5 | 848.0 | 32.0 | Back plate cracked, front still intact. |
| | | | | |
| AO Tourgard | 1.7 | 7.51 | 4.45 | No damage |
| | 2.3 | 10.16 | 4.45 | Damage |
| | 26.7 | 320.4 | 12.0 | Complete burn-through |
| | | | | |
| FS 1060-9 | 25.5 | 280.5 | 11.0 | Lens cracked |
| HD 112-4 | 25.5 | 38,250.0 | 1500.0 | Front surface intact, back surface began deteriorating at 2 sec of exposure |
| AF Visible Spectacle | 2.9 | 13.0 | 4.45 | No damage |
| | 3.2 | 14.29 | 4.45 | Damage |
| | 25.4 | 381.0 | 15.0 | Complete burn-through |
| | | | | |
| AF IR-1 | 1.3 | 5.66 | 4.45 | No damage |
| | 1.4 | 6.09 | 4.45 | Damage |
| | 25.6 | 59.9 | 2.34 | Complete burn-through |
| | | | | |
| AF Neodymium | 1.4 | 6.32 | 4.45 | No damage |
| | 1.5 | 6.59 | 4.45 | Damage |
| | 24.9 | 622.5 | 25.0 | Complete burn-through |
| | | | | |
| AF IR-3 | 27.0 | 820.0 | 30.0 | No damage |
| | 12.8 | 1148.0 | 90.0 | Damage |
| | 26.5 | 848.0 | 32.0 | Lens exploded |
| | | | | |

TABLE 9. DAMAGE THRESHOLDS FOR ARGON EXPOSURES

| Protector | Damage threshold power density (W/cm^2) | Absorption coefficient (cm^{-1}) | Comments |
|---------------------------|--|---|-----------|
| GO LGB | 5.8 | 13.52 | Dimpled |
| GO LGS-A | 10.2 | 14.57 | Dimpled |
| GO A-7448-1 | 6.9 | 12.80 | Dimpled |
| AO 599 | 286.9 | 3.87 | Blemished |
| AO 598 | 129.7 | 5.80 | Blemished |
| GO A7448-1-SS | 7.0 | 12.45 | Dimpled |
| AF Spectacle Goggle | 7.9 | 7.28 | Dimpled |
| SL Spectrogard | 121.8 | c | Blemished |
| AF Argon | 9.2 | 5.80 | Dimpled |
| AO Window Laminate | 17.7 | 12.53 | Dimpled |
| BL 5W3754 ^a | No DT | c | No effect |
| FS 515-7 ^b | 157.2 | >5.74 | Blemished |
| AF Multiband ^b | 10.0 | >9.36 | Dimpled |
| HD 112-5 ^b | 141.5 | >4.99 | Blemished |
| GO LGU-A ^b | 11.0 | >6.87 | Dimpled |

^aIrradiated at maximum power density of $286.9 \text{ W}/\text{cm}^2$.

^bAbsorption coefficient could not be calculated because optical density was $> 10 \text{ OD}$.

^cDichroic materials, absorption coefficient not applicable.

TABLE 10. ARGON EXPOSURES BURN-THROUGH DATA

| Protector | Exposure time (sec) | Power density (W/cm ²) | Comments |
|------------------------|------------------------|---------------------------------------|--|
| AO 598 | 1 | 286.9 | Surface blemish |
| AO 599 | 1 | 286.9 | Surface blemish |
| AO Window Laminate | 45 | 279.0 | Complete burn-through first layer, layers separated, dimple on back side of 2nd layer |
| BL 5W3754 | 1 | 286.9 | No damage |
| FS AL-515-7 | 40 | 55.0 | Cracked in half |
| GO LGB | 1 | 247.6 | Complete burn-through |
| GO LGS-A | 29 | 159.3 | Flamed immediately. Complete burn-through in 29 sec. |
| GO A-7448-1 | 3 | 159.3 | Flamed immediately. Complete burn-through in 3 sec. |
| GO A-7448-1-SS | 1 | 170.9 | Complete burn-through |
| GO LGU-A | 3 | 286.9 | Complete burn-through |
| AF Argon | 9 | 281.0 | Complete burn-through |
| AF Spectacle Goggle | 1 | 286.9 | Complete burn-through |
| AF Multiband | 1 | 279.0 | Complete burn-through |

TABLE 11. RUBY LASER EYEWEAR PROTECTORS: POWER DENSITY REQUIRED FOR DAMAGE

| Sample variety | Damage threshold (GW/cm ²) | Type of damage | Absorption coefficient (cm ⁻¹) |
|----------------|---|---------------------|--|
| HD 112-1 | 7.27 | Pitted | 35.5 ^d |
| AO 581 | 6.98 | Pitted | 20.5 ^d |
| AO 584 | 101.00 | Pitted | 19.2 ^d |
| AO 585 | 8.10 | Chipped | 28.0 ^d |
| BL 5W3756 | 0.271 | a | e |
| FS AL-633-5 | 48.20 | Chipped | 38.9 |
| GO R 7448-1-SS | 1.15 | Pitted | 80.4 |
| AO 580 | 7.70 | Pitted | 12.8 ^d |
| BL 5W3757 | 0.182 | Discolored | e |
| SL Spectrogard | 0.373 | b | e |
| AF Anti-Red | 1.78 | Discolored | 64.8 |
| GO LGS-R | 0.405 | Pitted | 104.8 |
| AO 588 | 5.80 | Pitted | 40.0 |
| GO LGS-R-SS | 0.242 | Pitted ^c | 151.5 |
| GO LGA | 0.371 | Pitted | 88.8 |
| GO R 7448-1 | 1.12 | Pitted | 66.7 |
| AO 586 | 8.26 | Discolored | 21.2 |
| GU LGU-R | 1.12 | Pitted | 63.1 |

^aDichroic layer burned.

^bDichroic layer darkened.

^cRippled appearance upon initial examination.

^dMultilayered with air spaces.

^eDichroic, absorption coefficient is not applicable.

TABLE 12. RUBY LASER EYEWEAR PROTECTORS: IRREVERSIBLE TRANSMITTANCE CHANGE

| Sample variety | Unexposed optical density | Percent of damage power density | Percent change OD | OD change |
|----------------|---------------------------|---------------------------------|-------------------|-----------|
| HD 112-1 | - | 0.45 | - | - |
| AO 581 | 7.00 | 0.68 | 0.0 | - |
| AO 584 | 5.49 | 0.52 | -0.9 | 0.05 |
| AO 585 | 7.10 | 0.46 | +1.7 | 0.12 |
| BL 5W3756 | - | 0.55 | - | - |
| FS AL 633-5 | 9.31 | 0.60 | -0.6 | 0.06 |
| GO R 7448-1-SS | 4.00 | 0.62 | +4.0 | 0.16 |
| AO 580 | 4.45 | 0.61 | -3.4 | 0.15 |
| BL 5W3757 | 8.09 | 0.63 | +0.7 | 0.06 |
| SL Spectrogard | - | 0.30 | - | - |
| AF Anti-Red | 6.24 | 0.49 | -0.5 | 0.03 |
| GO LGS-R | 7.32 | 0.47 | +0.5 | 0.04 |
| AO 588 | 6.64 | 0.51 | -2.3 | 0.15 |
| GO LGS-R-SS | 9.24 | 0.51 | +0.1 | 0.01 |
| GO LGA | - | 0.52 | - | - |
| GO R-7448-1 | 7.55 | 0.42 | +0.1 | 0.01 |
| AO 586 | 4.65 | 0.47 | -5.6 | 0.26 |
| GO LGU-R | 6.95 | 0.43 | -0.3 | 0.02 |

TABLE 13. REVERSIBLE BLEACHING RESULTS

| Mfg. ident. | Dye laser densitometer OD | Ruby laser densitometer OD | Percent of power density | %ΔOD |
|----------------|---------------------------------|----------------------------------|--------------------------------|--------|
| AF Anti-Red | 6.24 | 6.28 | 0.00038 | N/A |
| | | 6.27 | 0.00110 | - 0.20 |
| | | 6.28 | 0.00260 | 0.00 |
| | | 6.10 | 0.00410 | - 2.90 |
| | | 6.15 | 0.00700 | - 2.07 |
| | | 5.19 | 0.02800 | -17.36 |
| | | 5.32 | 0.02890 | -15.29 |
| | | 5.23 | 0.03500 | -16.83 |
| | | 3.84 | 0.11100 | -38.22 |
| | | 3.24 | 0.27100 | -48.08 |
| | | 2.89 | 0.37600 | -53.69 |
| | | 2.37 | 1.23000 | -62.02 |
| | | 1.86 | 2.01000 | -70.19 |
| | | 2.03 | 2.20000 | -67.47 |
| GO R 7448-1-SS | | 4.34 | 0.00310 | N/A |
| | | 4.34 | 0.02300 | 0.00 |
| | | 4.22 | 0.17900 | - 2.76 |
| | | 4.21 | 0.18300 | - 3.00 |
| | | 3.90 | 1.41000 | -10.14 |
| AO 586 | | 4.69 | 0.01500 | N/A |
| | | 4.66 | 0.12600 | - 0.64 |
| | | 4.49 | 1.61000 | - 4.26 |
| GO R 7448-1 | | 7.64 | 0.02800 | N/A |
| | | 7.44 | 0.25400 | - 2.62 |
| | | 7.51 | 1.93000 | - 0.92 |
| FS AL 633-5 | | 10.01 | 0.02300 | N/A |
| | | 10.30 | 0.06500 | + 2.90 |
| | | 10.33 | 1.10000 | + 3.20 |
| GO-LGU-R | 6.95 | 7.13 | 0.02300 | N/A |
| | | 7.01 | 0.17400 | - 1.68 |
| | | 7.00 | 1.15000 | - 1.82 |
| AO 580 | 4.45 | 4.32 | 0.01700 | N/A |
| | | 4.29 | 0.20900 | - 0.70 |
| | | 4.25 | 1.68800 | - 1.60 |
| HD 112-1 | | 10.34 | 0.30000 | N/A |
| | | 10.49 | 2.45000 | + 1.43 |
| AO 585 | 7.1 | 7.30 | 0.01500 | N/A |
| | | 7.25 | 0.13300 | - 0.68 |
| | | 7.40 | 1.64000 | - 1.37 |

TABLE 14. TEST PARAMETERS FOR FUME ANALYSIS

| Protector | Perforation time (sec) | Average laser power (W) |
|------------------------|---------------------------|----------------------------|
| AO Tourgard | 11 | 26.0 |
| Spectacle Goggle | 9 | 26.0 |
| IR-1 | 5 | 25.5 |
| GO A-7448-1 | 12 | 27.5 |
| R-7448-1 | 4 | 26.0 |
| LGB | 5 | 26.5 |
| LGS-R | 10 | 26.5 |
| LGS-HN-SS | 5 | 26.0 |
| SL Tan Frame | 9 | 26.5 |
| HD 112 Series Frame | 18 | 26.0 |

TABLE 15. RESULTS OF FUME ANALYSES IN PERCENT OF TOTAL GAS COLLECTED FROM VAPORIZED SAMPLES

| Compound | A0 lens | A0 Tourgard lens | AF goggles | AF spectacle | AF IR-1 lens | GO A-7448-1 lens | GO LGS-HN sideshield | GO R-7448-1 sideshield | SL tan frame | HD112 series frame | GO LGS-R lens | GO LGB lens |
|----------------------------------|------------|------------------------|---------------|-----------------|--------------------|------------------------|----------------------------|------------------------------|--------------------|--------------------------|---------------------|-------------------|
| ALDEHYDES | | | | | | | | | | | | |
| Acrolein | 3.657 | | 0.922 | 2.192 | 1.758 | 2.743 | 2.423 | 0.163 | 0.708 | 2.251 | 0.487 | |
| nPropanal | 6.576 | | | | | | | | | 1.334 | | |
| 2-Methylpropanal | | | | | | 1.874 | 0.327 | 0.219 | 1.142 | | | |
| Butanal | | | | 0.172 | | 2.487 | | | 0.373 | | | 0.376 |
| n-Hexanal | | | | | 0.884 | | 2.357 | | 0.837 | | | |
| 2-Ethylbutanal | | | | | | 1.178 | | | | | | |
| n-Heptanal | 3.674 | | | | 1.954 | | | | | | | |
| 2-Ethylhexanal | | | | | 4.596 | | | | | | | |
| Crotonaldehyde | | | 2.674 | 3.355 | | 8.282 | 5.107 | 2.885 | 4.481 | 0.655 | 6.992 | |
| | Total in % | 13.907 | 3.596 | | | | | 3.267 | 7.541 | 4.240 | 7.855 | |
| ALCOHOLS | | | | | | | | | | | | |
| Methanol | | 0.188 | 0.075 | 0.051 | 0.037 | 0.069 | 0.159 | 0.096 | | | 0.291 | 0.164 |
| Ethanol | | | | 0.154 | 0.075 | 0.942 | 0.228 | | | | | |
| Propanol | 1.408 | | | | | 2.115 | | | | | | |
| 2-Butyn-2-ol | | | | | | | | 1.459 | | | | |
| 4-Penten-1-ol | | | | | | 4.361 | 0.250 | 0.296 | | | | |
| 2-Methyl-1-Pentanol | | | | | | | | | | | | |
| 3-Methyl-1-Pentanol | | | | | | | | | | | | |
| trans-3-Hexene-1-ol | | | | | 0.812 | | | 0.713 | | | | |
| Isocctanol | | | | | | | | | | | | |
| 2-Ethylhexanol | | | | | | | | | | 7.063 | | |
| 4,8-Dimethyl-1-Nonanol | | | | | | | | | | 2.420 | | |
| 3-Butyn-2-ol | | | | | | | | | | | | |
| | Total in % | 1.596 | 0.075 | 0.205 | 0.924 | 7.487 | 0.637 | 2.564 | 9.483 | 0.291 | 0.510 | 0.674 |
| KETONES | | | | | | | | | | | | |
| Acetone | | 1.079 | | 0.533 | | 1.304 | | | | 1.136 | 0.553 | |
| Methyl Vinyl Ketone | | | | | 0.908 | | | | | 2.241 | | |
| 3-Pentanone | | | 0.840 | 2.711 | 0.830 | | | | | | | |
| 1-Acetoxy-2-Butanone | | | | | | | 0.689 | | | | | |
| 5-Hexene-2-one | | | | | | | | | | | | 3.752 |
| 3-Ethyl-4-Methyl-3-Pentene-2-one | | | | | | | | | | | | 1.195 |
| | Total in % | 1.079 | 0.840 | 3.244 | 1.738 | 1.304 | 0.689 | | | 3.377 | | 5.500 |

TABLE 15. (continued)

| Compound | A0 Tourgard lens | AF spectacle goggle | AF IR-1 lens | G0 A-7448-1 lens | G0 LGS-HN sideshield | G0 R-7448-1 sideshield | SL tan frame | HD112 series frame | G0 LGS-R lens | G0 LGB lens |
|--------------------------|------------------------|---------------------------|--------------------|------------------------|----------------------------|------------------------------|--------------------|--------------------------|---------------------|-------------------|
| PARAFFINS | | | | | | | | | | |
| Ethane | 0.020 | 0.004 | 0.014 | 0.015 | 0.010 | 0.018 | 0.030 | 0.030 | 0.041 | 0.014 |
| Propane | 0.048 | 0.009 | 0.139 | 0.147 | 0.268 | 0.196 | 1.024 | 0.317 | 0.023 | 0.005 |
| 2-Methylpropane | | | | | | | 0.063 | 0.099 | | |
| 2,7-Dimethyloctane | 0.068 | 0.013 | 0.153 | 0.162 | 0.278 | 0.214 | 1.117 | 0.446 | 0.064 | 2.636 |
| Total in % | | | | | | | | | | 2.655 |
| OLEFINS | | | | | | | | | | |
| Acetylene | | | | | | | 0.006 | | | |
| Ethene | 0.010 | 0.003 | 0.006 | 0.006 | 0.016 | 0.009 | 0.011 | 0.027 | 0.027 | 0.027 |
| Propene | 0.039 | 0.004 | 0.480 | 0.754 | 0.381 | 0.984 | 2.123 | 0.428 | 0.043 | 0.009 |
| 2-Methylpropene | 5.094 | | | | | 2.700 | 2.948 | | | |
| 2-Butyne | 3.539 | 1.218 | | 0.116 | | 1.115 | 3.974 | | | |
| 1-Butene | | 2.052 | 3.284 | 3.060 | 4.181 | 0.176 | 0.848 | 5.379 | 2.053 | 0.970 |
| cis-2-Butene | | 2.102 | | 1.920 | | | | | | |
| trans-2-Butene | | | 2.303 | | | | | | | |
| 1-Pentyne | 5.894 | | | | | | 3.190 | 3.077 | | 0.549 |
| 1-Pentene | | | | | | 1.126 | 1.391 | | | |
| cis-Pentene-2 | | | | | 2.329 | | | | | |
| 1-Hexene | 7.017 | 2.248 | 1.073 | 1.127 | 1.331 | 2.692 | 1.178 | 4.775 | 3.292 | |
| 2-Ethyl-Hexene-1 | | 15.035 | 14.871 | 14.234 | 9.819 | 4.654 | 46.669 | 3.536 | 49.263 | 51.170 |
| 1-Octene | | | | | 1.158 | | | 1.196 | | |
| 1-Nonene | | | | | | | | 2.996 | | |
| 3,4,4-Trimethyl-2-Hene | | 0.022 | | | | | 1.335 | | 1.180 | |
| 5-Methyl-cis-2-Pentene-2 | | | | | | | | | 1.944 | |
| 3-Hexyne | | | | | | | | | 2.291 | 5.599 |
| trans-3-Heptene | 21.593 | 22.684 | 22.017 | 21.157 | 19.215 | 13.463 | 63.673 | 21.414 | 60.093 | 58.324 |
| Total in % | | | | | | | | | | |
| DIOLEFINS | | | | | | | | | | |
| Allene | | | | | | | | | | |
| 1,3-Butadiyne | | | 0.299 | 0.195 | | 0.059 | | | | |
| 1,3-Butadiene | | | 2.787 | 2.149 | 4.336 | | | | 1.631 | |
| 2-Methyl-1,3-Butadiene | | 0.878 | | | | 0.355 | | | | |

TABLE 15. (continued)

| Compound | AO Tourgard lens | AF spectacle goggle | AF lens | GO A-7448-1 lens | GO LGS-HN sideshield | GO R-7448-1 sideshield | SL tan frame | HD112 series frame | GO LGS-R lens | GO LGB lens |
|---|------------------------|---------------------------|----------------|------------------------|----------------------------|------------------------------|--------------------|--------------------------|---------------------|-------------------|
| DIOLEFINS (Cont) | | | | | | | | | | |
| 1,2-Pentadiene | 1.536 | | | | | | | 1.731 | | |
| 1,4-Pentadiene | | 0.566 | 0.592 | | | | | | | |
| 2,3-Pentadiene | | | | 0.662 | | | | 0.516 | 0.796 | |
| 1,5-Hexadiene | | | | | | | | | | 1.630 |
| Isoprene | | | | | | | | | | 0.820 |
| 1,4-Hexadiene | | | | | | | | | | 2.450 |
| 4-Methyl-4-Hexadiene | 1.536 | 1.444 | 3.678 | 3.006 | 4.336 | 0.414 | | 16.506 | 2.427 | |
| Total in % | | | | | | | | | | |
| NAPHTHALENES | | | | | | | | | | |
| 1,1-Dimethylcyclopropane | | | | | | | 0.221 | | | |
| trans-1,2-Dimethylcyclopropane | | 0.983 | 1.040 | 1.166 | | | | | | |
| Cyclopentadiene | | | | | 3.584 | | | 5.856 | | |
| 3-Methylcyclopentene | | | | | | | | | | |
| 1-trans-2-Dimethylcyclopentane | 9.149 | | | | | | | | | |
| 3-Methyl-1-cyclohexene | | 0.038 | | | | | 0.588 | | | |
| 3-Ethylcyclo-pentene | | | | | | | 2.040 | | | |
| 6,6-Dimethylfulvene | | | | | | | | | | |
| 1-trans-2-cis-3-Trimethyl- cyclohexane | 21.653 22.674 | 2.069 3.109 | 2.038 3.204 | | | 19.289 19.289 | 4.461 | 5.856 | | |
| Total in % | 9.149 | | | | | | | | | |
| AROMATICS | | | | | | | | | | |
| Benzene | | | | | | | | | | |
| Toluene | | | 2.775 | | 46.120 | | 9.615 | 16.291 | 4.323 | 4.101 |
| Xylene | | | | | 3.782 | | 4.685 | 5.537 | 2.621 | 1.548 |
| Styrene | | | 1.108 3.883 | 0.295 0.295 | | | 1.892 | | 1.793 8.737 | |
| Total in % | | | | | 49.902 | | 16.192 | 21.828 | | 5.649 |
| ACIDS | | | | | | | | | | |
| Acetic Acid | 0.496 | 2.823 | | 0.043 | | 3.870 | | | | |
| Propionic Acid | 48.293 | 39.602 | 49.931 | 41.468 | | 52.579 | | | | |
| Phenol | | 0.532 | | | | 56.449 | | | | |
| Total in % | 48.789 | 42.957 | 49.931 | 41.511 | | | | | | |

TABLE 15. (continued)

| Compound | A0 Tourgard lens | AF spectacle goggle | AF lens | GO A-7448-1 lens | GO LGS-HN sideshield | GO R-7448-1 sideshield | SL tan frame | HD112 series frame | GO LGS-R lens | GO LGB lens |
|----------------------------|------------------------|---------------------------|------------|------------------------|----------------------------|------------------------------|--------------------|--------------------------|---------------------|-------------------|
| ESTERS | | | | | | | | | | |
| Vinyl Acetate | 0.544 | | | | | | | 2.663 | | |
| 2-Phenylethyl Formate | | | | | | | | | 1.851 | 2.032 |
| Vinyl Propionate | 0.544 | | | | | | | 2.663 | 1.851 | 2.032 |
| Total in % | | | | | | | | | | |
| ETHER | | | | | | | | | | |
| 2,3-Epoxybutane | | | 0.742 | | 1.837 | | | | 2.247 | 3.063 |
| Vinyl isobutyl ether | | | 0.742 | | 1.837 | | | | 2.247 | 3.063 |
| Total in % | | | | | | | | | | |
| NITROGEN CONTAINING | | | | | | | | | | |
| Isocapronitrile | | | | | | | 1.108 | 0.978 | | |
| Imidazole | | | | | | 0.170 | | | | |
| Neopentyl Nitrate | | | | | | 0.170 | 1.108 | 0.978 | | 0.818 |
| Diazomethane | | | | | | | | | | 0.818 |
| Total in % | | | | | | | | | | |
| HALOGEN CONTAINING | | | | | | | | | | |
| Chloromethane | 0.005 | 0.004 | 0.069 | 0.053 | 0.148 | 0.018 | 0.241 | 0.025 | | |
| Vinyl Chloride | | | | | | | 0.105 | | | |
| 2-Chloropropane | | | | | | 0.612 | 0.131 | | | |
| 1-Chloro-3-Methylbutane | | | | | | | | 2.240 | | 1.736 |
| Chlorobenzene | | | | | | | | | | 1.736 |
| 2-Bromobutane | | | | | | | | | | 8.808 |
| Total in % | 0.005 | 0.004 | 0.069 | 0.053 | 0.148 | 0.630 | 0.477 | 2.265 | | |
| | 1.735 | 5.711 | 9.615 | 23.353 | 3.628 | 2.938 | 7.139 | 11.019 | 16.672 | |
| TOTAL IN % | 100.001 | 99.998 | 100.001 | 99.999 | 100.001 | 100.000 | 99.998 | 99.999 | 99.999 | 99.564 |
| UNKNOWN | | | | | | | | | | |

TABLE 16. IMPACT RESISTANCE TEST RESULTS--ANSI Z87.1

| Manufacturer/Type | Section 6.1.1.4.6(2) 7/8 in. (2.22 cm) diameter at 50 in. (1.27 m) | | 5.1.4.1.6(4) 5/8 in. (1.588 cm) diameter at 39.3 in. (1 m) | |
|----------------------|--|------|--|------|
| | PASS | FAIL | PASS | FAIL |
| AO 580 | | X | X | |
| 581 | | X | X | |
| 584 | | X | | X |
| 585 | | X | | X |
| 586 | X | | | |
| 587 | X | | X | |
| 588 | | X | X | |
| 598 | X | | X | |
| 599 | | X | X | |
| 680 | | X | | X |
| 698 | | X | | X |
| Tourgard | X | | | |
| Window Laminate | X | | | |
| BL 5W3754 | | X | X | |
| 5W3755 | | X | X | |
| 5W3756 | | X | X | |
| 5W3757 | | X | | X |
| 5W3758 | | X | | X |
| FS AL-515-7 | X | | X | |
| AL-633-5 (Plate) | | X | | X |
| AL-633-5 (Goggle) | X | | | |
| AL-1060-9 | | X | | X |
| GO LGA | X | | | |
| LGB | X | | | |
| LGS-NDGA | X | | | |
| LGS-A | X | | | |
| LGS-R | X | | | |
| LGS-HN | X | | | |
| LGS-NN | X | | | |
| A 7448-1 | X | | | |
| NDGA 7448-1 | X | | | |
| HN 7448-1 | X | | | |
| R 7448-1 | X | | | |
| LGU-A | X | | | |
| LGU-R | X | | | |
| LGU-NDGA | X | | | |
| LGU-HN | X | | | |
| HD 112-1 | | X | | X |
| 112-2 | | X | | X |
| 112-4 | | X | X | |
| 112-5 | | X | X | |
| AF Spectacle | X | | | |
| Goggle | | | | |
| Visible | X | | | |
| Spectacle | | | | |
| IR-1 | X | | | |
| Neodymium | | X | | X |
| Anti-Red | | X | X | |
| Argon | | X | X | |
| Multiband | | X | X | |
| IR-2 | | X | | X |
| IR-3 | X | | | |
| SL Spectrogard | | X | X | |